FINAL REPORT
ON
A STUDY OF THE AIR-VOID CHARACTERISTICS OF HARDENED CONCRETE

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Joint Highway Research Project

by

F. K. FEARS

PURDUE UNIVERSITY
LAFAYETTE INDIANA

FINAL REPORT

A STUDY OF THE AIR-VOID CHARACTERISTICS

OF HARDENED CONCRETE

TO: K. B. Woods, Director
Joint Highway Research Project

January 24, 1957

FROM: Harold L. Michael, Assistant Director

File: 5-8-17
C-36-37 Q

Attached is a final report entitled, "A Study of the Air-Void Characteristics of Hardened Concrete." This report has been prepared by Mr. Fulton Fears, former graduate assistant of the Project, under the direction of Professor D. W. Lewis and with the assistance of Mr. J. F. McLaughlin.

This report presents the results of an investigation of the air-void characteristics of hardened concrete and the correlation between certain air-void characteristics and durability. The study was initiated and data collected at Purdue University and completed in absentia by the author.

Respectfully submitted,

Harold L Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:hgb

Attachment

cc: J. R. Cooper
J. T. Hallett
F. F. Havey
Lloyd Poindexter
C. E. Vogelgesang
G. A. Hawkins
D. S. Berry
G. A. Leonards
R. E. Mills
B. H. Petty
J. L. Waling

FINAL REPORT

A STUDY OF THE AIR-VOID CHARACTERISTICS OF HARDENED CONCRETE

by

Fulton Keller Fears
Graduate Assistant

Joint Highway Research Project
Project C-36-37 Q
File 5-8-17

Purdue University
Lafayette, Indiana

January 24, 1957

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The interest and encouragement of Professor K. B. Woods have been of particular value.

The help of Mr. J. F. McLaughlin in bringing this investigation to a successful completion is greatly appreciated.

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ABSTRACT

Fears, Fulton Keller. Ph. D., Purdue University, January, 1957. A Study of the Air-Void Characteristics of Hardened Concrete. Major Professor: K. B. Woods.

The theory of the action of entrained air in producing frost-resistant concrete demonstrates the importance of the size and distribution of the air voids in the portland-cement paste. In this investigation the linear traverse technique was used to determine the air-void characteristics of hardened concrete. The characteristics investigated were: (a) Air content, total volume of voids per unit volume of concrete; (b) Number of voids intersected per unit length of traverse; (c) The specific surface of the air voids, the surface area of the voids per unit volume of air; (d) Number of hypothetical spheres of equal radius having the same volume of air per unit volume of concrete and the same specific surface as the actual system of random sized voids; and (e) Spacing factor, distance from void boundary to outer boundary of sphere of influence. To compute the void-spacing factor for the hypothetical void system each sphere is considered to be at the center of a cube with the sum of the volumes of all such cubes and the enclosed spheres equaling the combined air and paste content of the concrete. The sphere of influence of each void is the radius of the sphere circumscribing the hypothetical cube. The air content and the number of voids per unit length of traverse were measured directly. The remaining characteristics were computed from these two measurements with the paste content being introduced in the computation of the spacing factor.

Statistical methods were applied to the study of the variability of

the air content and number of voids per inch within a concrete beam 3 x 4 x 16 inches. The analysis showed that the measurement of these characteristics for a particular beam may be considered as one long traverse without regard to the position or length of the individual traverses. To determine the air content within ±0.5 percent of the true value at the 90 percent confidence level a total length of traverses of 200 inches is suggested.

Forty cores taken from a concrete pavement were examined. The study of the variability of the air content and number of voids per inch as shown by these cores suggests that for the sampling of pavements, cores be taken at random along the stretch of pavement and measurements made on one surface of each core.

Thirty-eight beams from nineteen mixes were used to study the correlation between each of the five air-void characteristics and durability. These beams had shown varying degrees of durability as measured by resistance to deterioration in laboratory freezing and thawing tests. Durability factors were used to express the durability of each of these beams. The five air-void characteristics ranked in the order of their correlation with durability beginning with the one showing the best correlation are: (1) spacing factor, (2) specific surface, (3) number of voids per inch, (4) hypothetical number of voids per cubic inch, and (5) total air content.

The spacing factor and the specific surface were found to be of almost equal importance in producing durable concrete. Hence, either of these two characteristics may be used as a criterion for determining the air requirements for frost-resistant concrete.

INTRODUCTION

Numerous investigators have reported (4, 5, 7, 10, 11, 14, 15, 24, 32)* laboratory studies showing increases in durability and resistance to scaling which result from entraining air in the concrete mix. Several of these studies (4, 5, 7, 11) show that the durability of concrete made with poor aggregates is sometimes greatly increased by air entrainment. Andrews' report (3) of the performance of concrete test roads in the northeastern states built with a wide range of variables shows a comparison of the field performance of air-entrained concrete with adjacent sections of the same construction but without air entrainment. The report shows that high resistance to the severe exposure of repeated cycles of freezing and thawing and salt action in ice removal has been given to these concrete pavements over a period of ten to fourteen years by air entrainment. Jackson (12) and Gonnerman (10) report that the performance under service conditions of experimental paving projects constructed with air-entrained portland cement parallels the results of the laboratory studies. Thus the superior performance in general of air-entrained concrete has been demonstrated in both the field and the laboratory.

Purpose and Scope of Study

Reports of research on air entrainment deal principally with factors which control the amount of air or with changes in properties of the concrete related to changes in the gross amount of air. However, theoretical and practical considerations suggest that the properties of

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*Numbers in parentheses refer to references listed in the Bibliography.

the air voids themselves are important factors influencing the ability of concrete to withstand freezing and thawing conditions (15, 18, 19, 20, 21).

Considerable research on the effect of air entrainment on the durability of concrete beams as measured by resistance to deterioration under repeated cycles of freezing and thawing has been performed in the laboratories of the Joint Highway Research Project at Purdue University. The studies reported by Blackburn (5) and Bugg (7) show increases in the laboratory durability of air-entrained concrete made with limestone aggregates which have poor to fair field service records over concrete made with the same materials but without the inclusion of air.

Subsequent studies of the effect of air entrainment on the durability of concrete made with aggregates with poor to fair field performance records have shown at times considerable differences in durability between beams from the same mix and between mixes using the same materials and which have the same total air content as determined by measurements on the fresh concrete. Hence, this study was initiated to determine which property of the air voids is most significant in producing durable concrete and to what extent these differences in durability between beams fabricated from the same materials under similar conditions can be explained by differences in the air-void characteristics of the beams. The air-void characteristics either measured or calculated were: (a) total air content, (b) number of voids intersected per inch, (c) specific surface, (d) hypothetical number of voids per cubic inch, and (e) void spacing factor.

The investigation was divided into three phases. In the first phase of the work, beams made in the laboratory were examined for the

purpose of developing the techniques to be followed in the study of the air-void characteristics. In the second phase cores taken from two concrete pavements were examined for the purpose of studying the variability of the air content of pavements. In the third phase laboratory-fabricated beams which had shown unexplained differences in durability as measured by resistance to deterioration in freezing and thawing tests were studied for the purpose of providing a possible explanation for these observed differences.

The cores examined in the second phase of the study came from concrete pavements which were constructed without the purposeful entrainment of air. One-half the cores came from a pavement in which a limestone aggregate with a poor field performance record was used. The remainder of the cores were taken from a pavement in which a gravel aggregate with a good field performance record was used. The reason for choosing these pavements was to determine to what extent, if any, this difference in field performance could be attributed to a difference in air-void characteristics resulting from the accidental entrapment of air in the concrete mix.

Survey of Literature

The literature concerning the effects of air entrainment on concrete strength, workability, permeability, and durability is voluminous. In this section, the literature pertinent to the theories of the action of the air voids in producing durable concrete and the measurement of the air-void characteristics of hardened concrete is reviewed.

Theory

Entrained air appears to exist in the form of small, disconnected

air bubbles distributed throughout the concrete paste (26). The natural voids found in concrete made without an air-entraining agent vary considerable among different mixes but are generally larger than the bubbles produced by air entrainment (21). These natural voids result from the entrapping of air in the concrete mix. In air-entrained concrete the composite system of voids is a combination of the natural voids and air-entrained bubbles. Warren (29) found that the average diameter of the voids for a series of air-entrained mixes varied from 0.04 millimeter to 0.10 millimeter.

Powers and Helmuth (18, 20) explain the freezing of water in hardened portland-cement paste in terms of two mechanisms: (a) the generation of hydraulic pressure as water freezes in capillary cavities, and (b) the growth of bodies of ice in the capillary cavities or air voids by diffusion of water from the gel pores. A brief review of these two mechanisms follows.

Hardened portland-cement paste is made up of extremely tiny spheres linked together to form the cohesive mass called cement gel. When the cement gel completely fills the space available to it the porosity of the paste is about 25 percent. In most pastes the volume of the gel does not equal the apparent volume. The unfilled space in the paste occurs as cavities which are called capillary pores. The gel pores are the interstitial spaces among the massed spheres which surround the cavities.

The gel pores are so small that water cannot freeze in them at ordinary temperatures. Thus, at these temperatures, the capillary pores or cavities are the only places where ice can exist within the boundaries of the paste. However, the capillary pores are also so

small that the ice crystals which they contain can exist only when the temperature is below the normal freezing point. Air voids such as those in air-entrained concrete are extremely large compared with the capillary pores and gel pores in the paste.

In a water-soaked paste the capillary pores and the gel pores are full, or nearly full, of water. When the water in a saturated capillary pore begins to change to ice the volume of the water plus ice will exceed the original capacity of the cavity. This comes about because one cubic centimeter of water occupies about 1.09 cubic centimeters of space after freezing. Therefore, during the time the water is changing to ice, the cavity must dilate or the excess water must be expelled from it. Although the coefficient of permeability of the cement gel is extremely low there is the possibility that the excess water can escape from the cavity during freezing. The growing ice body in the capillary cavity may be considered as a sort of pump forcing water through the cement gel toward an air-void boundary. Such a pumping action involves the generation of pressure. In general, during the process of freezing, hydraulic pressure will exist throughout the paste, and this pressure will be higher the farther the point in question from the nearest air-void boundary. By reducing the distance between voids to the point where the protected shells surrounding air voids overlap, the generation of disruptive hydraulic pressure during the freezing of water in the capillaries can be prevented.

The generation of hydraulic pressure through the above mechanism does not account for all the phenomena that accompanies freezing. Powers and Helmuth (20) suggest that part of the effect of freezing is due to the tendency of microscopic bodies of ice to grow by diffusion

of water from the gel pores to the capillary cavities, producing expansion. This may occur at any temperature below the temperature at which the ice in a cavity was formed.

The functions of the entrained-air voids are (a) to limit the hydraulic pressure in the paste during the initial stages of freezing; and (b) to limit or prevent the growth of microscopic bodies of ice in the paste while the temperature is below the normal freezing point. Powers (19) has derived a formula from which can be calculated the theoretical maximum distance from any point in the paste to an air-paste interface which can occur without disruptive hydraulic pressure being generated. For this void spacing factor he has suggested an upper limit of 0.01 inch. This value he also considers satisfactory for the prevention of damage due to the growth of ice bodies.

Powers (19) has derived an equation, based on measurements of air-void characteristics of hardened concrete made by the linear traverse method, for a spacing factor which may be used to characterize the bubble system of a specific sample of concrete. This spacing factor is applied to a hypothetical bubble system which has the same total volume and surface area of bubbles as the actual system but which differs radically in the total number of bubbles. In the derivation of this spacing factor the assumption is made that the aerated paste volume is divided into continuous cubes of equal size, and that each cube contains one air bubble so placed that the bubble and cube centers coincide. The spacing factor is then the distance from a corner of the cube to the surface of the bubble measured along a diagonal.

Warren (29) has presented a technique by which it is possible to determine the characteristics of air voids in concrete by means of the

plane-intercept method. This procedure gives the true number of bubbles in the paste, and, hence, a true average void spacing factor.

Lord and Willis (17) have also presented a procedure by which the true number of bubbles in the paste may be computed using a linear traverse. However, to obtain the true number of bubbles by using the linear traverse technique it is necessary to measure the length of the individual chord intercepts.

The Linear Traverse Technique

Lincoln and Rietz (16) in an article in Economic Geology in 1913 reviewed the development of the mensuration methods used in the measurements of the minerals in a rock. They report that the first mensuration method to make use of physical measurements was the areal method of Delesse in 1848. Delesse applied a transparent sheet of paper of goldbeaters' skin to the polished or nearly plane surface of a rock and traced upon it the outline of the various mineral grains. The sketch was then tinted so that the various minerals could be identified, and the sheet pasted with soluble gum to a piece of tin foil. The variously tinted surfaces with their adhering tin foil were next cut apart and grouped according to their colors, the paper washed away, the tin foil particles in each group weighed, and the percentages of the various mineral compounds of the rock computed directly from these weights.

The linear mensuration method was devised by Rosiwal (23) in 1898. It consisted of measuring the intercepted lengths of grains along a line or series of lines and calculating the percentage by volume by dividing the total distance into the sum of the intercepts for each component. Rosiwal presented a proof by calculus to show that intercepts on lines

are proportional to volumes. Lincoln and Rietz (16) presented an alternate geometrical proof. The Rosiwal method as applied to the determination of the percentages of minerals in a rock was carefully studied by Johannsen and Stephenson (13).

Shand (25) developed a recording micrometer which served both to make the measurements and to add the resulting figures and which was used to determine the mineral composition of rocks as revealed by the microscope in thin sections. An important defect in the apparatus devised by Shand was that it could be used to measure but two constituents at one time--any one mineral and the remainder of the rock. Wentworth (30) improved on the recording micrometer by developing an accessory stage whereby separate micrometers accumulated intercepts for assigned minerals.

The methods which have been used for the measurement of air in hardened concrete have been based on the procedures followed by the geologists in the measurement of minerals in rocks. Verbeck (26) reported a visual method for determining the amount of air by planimetering camera lucida tracings of polished sections. Warren (29) used a procedure whereby the air voids exposed by a polished surface were filled with a flucrescent material and photographed under ultra-violet light. Measurements were then made on the photographs to determine the air-void parameters. Rexford (22) observed thin sections of the concrete paste and made the measurements with the Wentworth recording micrometer.

Brown and Pierson (6) used the principle of the Wentworth recording micrometer to construct a mechanical integrator of special design with two recording motions--one for the air voids and one for the solids. This instrument is used in conjuction with a binocular microscope,

generally working at 30x to 45x magnification. The use of this apparatus permits the observation of surfaces large enough to afford true representation of aggregate and also of the occasional large air void that occurs in practically all concretes. The binocular microscope greatly facilitates the perception of air voids. The amount of work involved in the preparation of the specimen surface is less than that required by the other methods. Therefore, equipment and procedures similar to those recommended by Brown and Pierson were used in this study.

DEVELOPMENT OF TECHNIQUES FOR THE DETERMINATION OF AIR-VOID CHARACTERISTICS OF HARDENED CONCRETE

The apparatus and procedure followed in the determination of the air-void characteristics of hardened concrete are similar to those reported by Brown and Pierson (6). A visit to the Research and Development Laboratories of the Portland Cement Association in Chicago was made at which time Dr. Brown demonstrated the equipment and methods being used.

Linear Traverse Integrator

The apparatus for the measurement of the air content and the number of voids per inch is shown in Figure 1. Mr. Gerald M. Batchelder, while employed as a Graduate Research Assistant by the Joint Highway Research Project, prepared the detailed drawings and supervised the construction of the linear traverse integrator. In the description which follows each part is referenced to Figure 1 by means of a letter in parentheses.

The three principal parts which make up the linear traverse integrator are the grooved base plate (A), the lower front and back rails (B) to which the middle plate (C) is attached, and the upper front and back rails (D) carrying the top plate (E) on which the concrete specimen (F) is placed. The lower rails ride in two grooves in the base plate. The front groove (G) is rectangular in shape while the back groove (H) is V-shaped to aline and guide the rails.

The main lead screw (I) is attached to the base plate by two bearing blocks (J). At the right end is a revolution counter (K) which is used to record the distance traveled by the lower rails and middle plate which represents the distance across the solid constituents of the

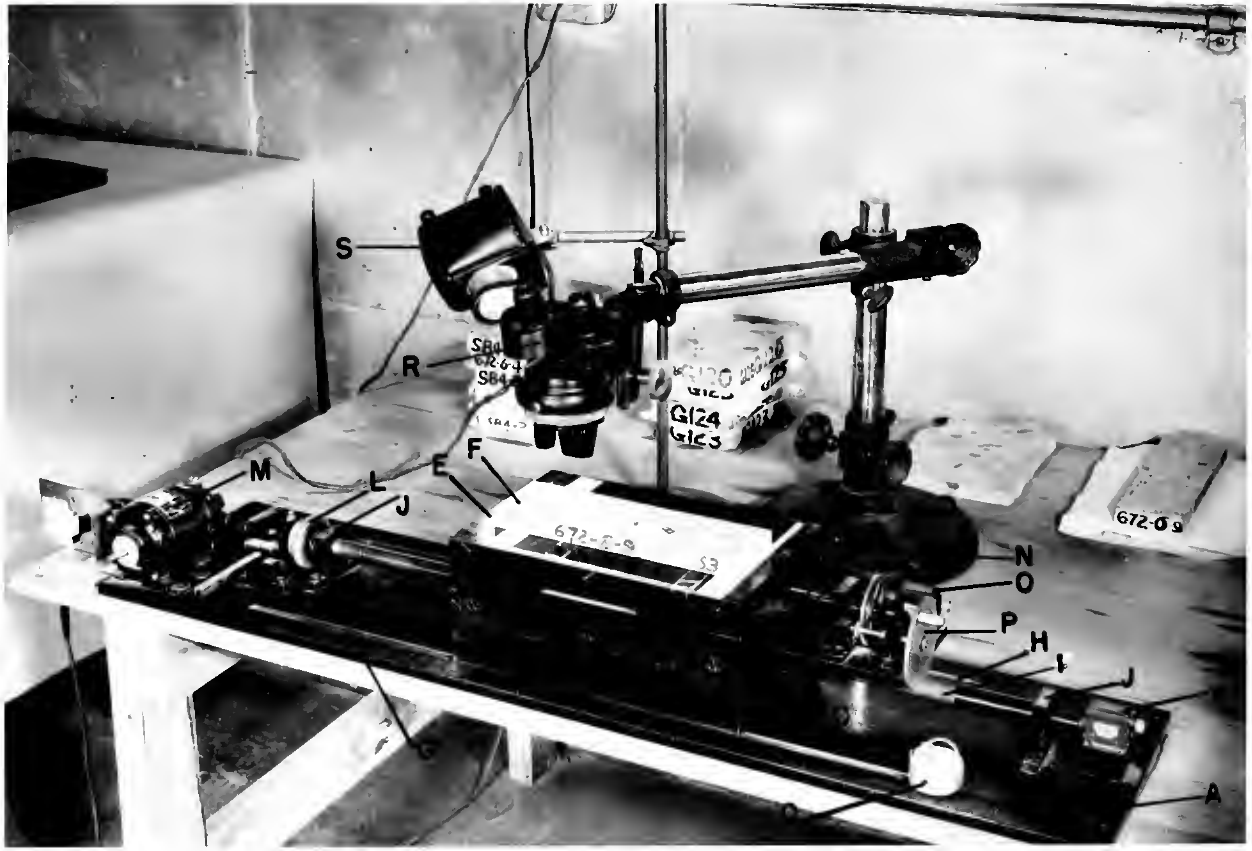


FIG. 1 LINEAR TRAVERSE INTEGRATOR

concrete. Power is supplied either manually by a knurled wheel (L) or by an electric motor (M) at the left end of the screw. One revolution of the main lead screw produces a tenth of an inch of translation.

The middle plate, to which the lower rails are attached, carries the top plate lead screw (N), a second revolution counter (O), and a hand wheel (P) for controlling the movement of the top plate relative to the middle plate. The second revolution counter is used to record the distance across the air voids in the concrete. One revolution of the top plate lead screw produces a hundredth of an inch movement of the top plate. A ratchet counter (Q) is used to tally the number of air voids encountered in a traverse.

A binocular microscope (R) is used with 3X objective lenses and 15X eyepieces to produce a magnification of 45 diameters. Crosshairs intersecting at 90 degrees are mounted in one eyepiece so that the crosshairs make an angle of 45 degrees with a line in the direction of movement of the intersection. A spotlight-type microscope lamp (S) is positioned to throw a beam of light on the specimen at a low angle so that the shadows facilitate the recognition of the air voids.

In using the linear traverse integrator the concrete specimen is moved to the right or left as desired by means of the main lead screw until, through the microscope, the observer sees an air void coming into the field of view. He stops the motion with the main lead screw when the intersection of the crosshairs is at the edge of the air void. He then uses the hand wheel on the middle plate to move the intersection of the crosshairs to the opposite edge of the air void, and one void is tallied on the ratchet counter. Motion is resumed with the main lead screw until the intersection reaches another air void and the process

is repeated. A small scale is used to measure the distance from the edge of the top plate to the concrete specimen in order to obtain uniformly spaced traverses.

The distance in inches across the solid components is found by dividing by ten the number of revolutions recorded on the revolution counter at the right end of the main lead screw. The distance across the air voids in inches is obtained by dividing by one hundred the reading on the second revolution counter. The sum of the two distances gives the total length of the traverse. The distance across the air voids divided by the total length of the traverse is an estimate of the total air content of the concrete. The number of voids per inch is computed by dividing the total number of voids by the total length of the traverse.

Preparation of Surface of Concrete Specimen

Slabs approximately one inch thick were cut from the concrete specimens by means of the masonry saw shown in Figure 2. A wet-cutting steel bond diamond blade was used on the saw. The size of the beams from which the slabs were cut was 3 x 4 x 16 inches. First, approximately three inches were removed from each end of the beam. Then longitudinal cuts were made through the three-inch dimension to produce a one-inch slab from the center portion of the beam. The sawed surfaces, approximately 3 x 10 inches, on each side of the slab were used for determining the air-void characteristics of the beam. Modifications in sawing were necessary depending on the degree of deterioration of the individual beam. A typical beam and slab are shown in Figure 2.

For the sawing of slabs from concrete cores taken from pavements

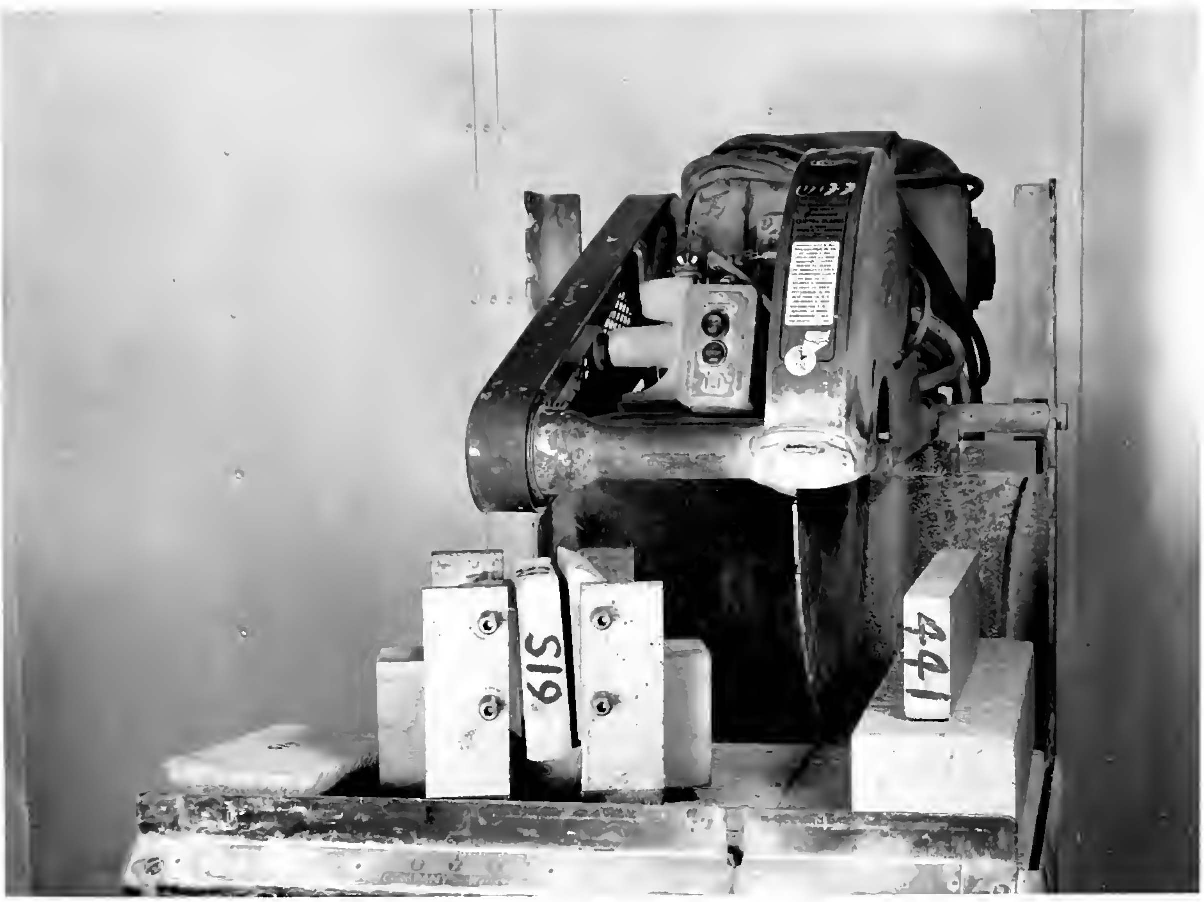


FIG. 2 MASONRY SAW

the jig shown in Figure 2 was designed. This jig consists of four angles attached to a ½-inch steel plate. Two notched 2 x 4-inch timbers were used to support the core with four ½-inch Allen-head screws through the angles being used to prevent rotation. When a cut was made on one side of the slab the outside portion of the core was removed and replaced with a wooden block which was fitted closely to the newly sawed surface in order to aid in holding the remainder of the core in place while the final cut was being made.

The same procedure was followed for polishing the surfaces of the slabs from both the beams and cores. The initial polishing was done on hard plate glass 24 inches square using Grade No. 100 aluminum oxide power for concrete made with gravel aggregate and Grade No. 180 with crushed stone aggregate. Water was used as a lubricating and dispersing medium during grinding and for washing the polished surface. After twenty minutes of polishing, the surface was thoroughly washed using a nozzle to produce a pressure to aid in removing the grinding powders from the voids. The washing procedure was repeated after another twenty minutes of polishing.

The above procedure was then repeated using Grade No. 240 aluminum oxide powder with both gravel and stone aggregate concrete. Thus, a total of eighty minutes was spent in polishing on each surface with two grades of grinding powders.

The final polishing was done with the portable belt sander shown in Figure 3. The wooden jig, also shown in Figure 3, was used for holding the slabs in place while the polishing was being done. Silicon carbide abrasive belts Grit No. 240 were used. One belt was used to polish two surfaces alternating between the two surfaces so that a total of ten

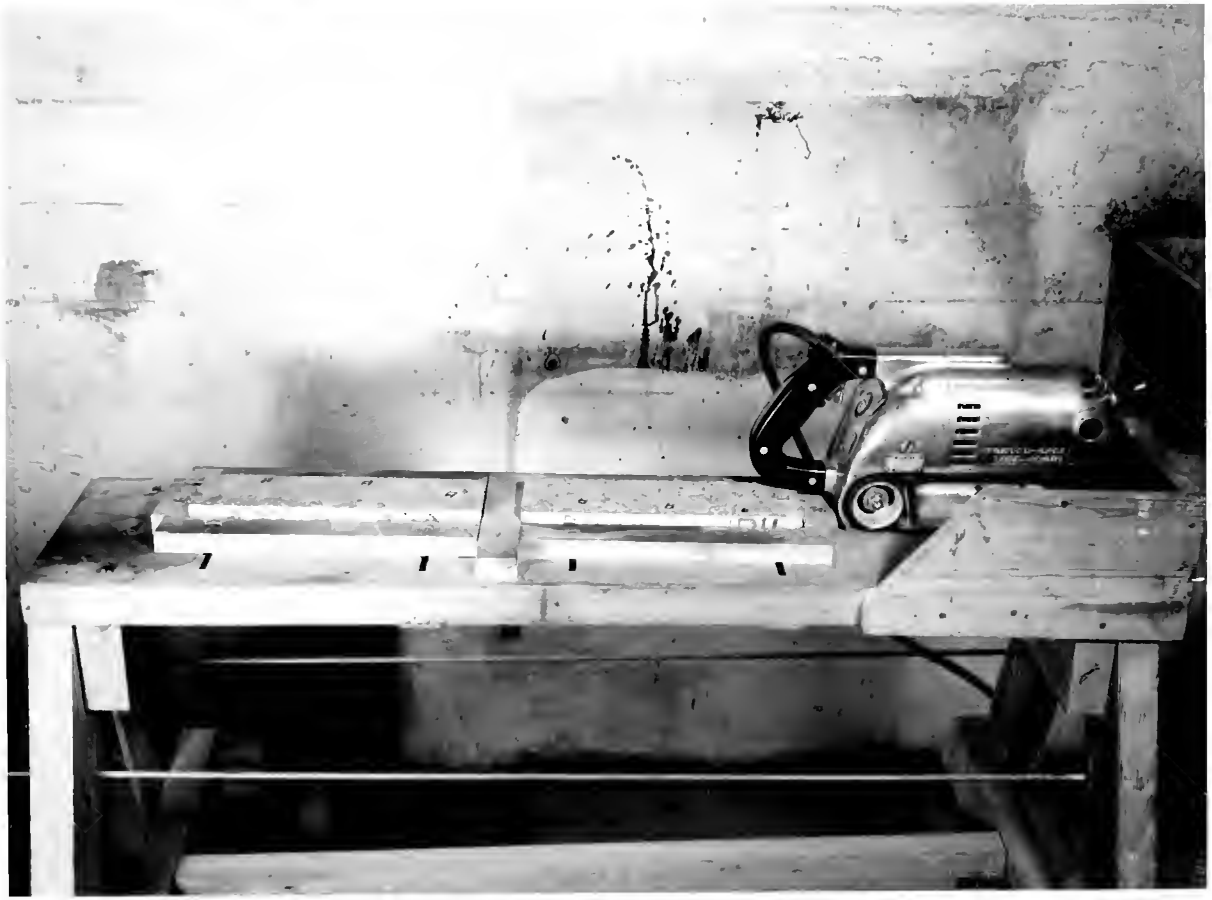


FIG. 3 PORTABLE BELT SANDER

minutes of polishing was done on each surface.

This procedure produced polished surfaces on which the voids were sharply defined and measurements on a given traverse could be repeated with practically the same result for the air content and the number of voids per inch.

Position and Length of Traverse

The Rosiwal method of determining the percentage by volume of the constituents of a solid requires that a random line be passed through the solid. This principle is applied to a sample of concrete by first exposing a random section and then running a random traverse line in the plane of the section. In the actual application to a given beam the four surfaces of the beam are considered to have been randomly selected with respect to the concrete mix from which the beam was made.

In order to determine the effect, if any, of the position of the traverse within the beam an investigation of the variability of the air content and number of voids per inch within the beam was made. Also, the effect of the length of traverse on the reliability of the measurements was studied. For this investigation two beams from a concrete mix in which an aggregate with good field performance and laboratory records was used were selected for examination. Each of these beams had withstood 800 cycles of freezing and thawing without any loss in dynamic modulus of elasticity.

The original beam dimensions were 3 x 4 x 16 inches. Three inches were removed from each end of the beams by sawing. Then three cuts were made longitudinally through the three-inch dimension so that four slabs approximately 3/4-inch thick were produced from each beam. Three

surfaces from each beam were polished for examination by the linear traverse integrator. The three surfaces selected for examination were those which could be considered to represent three vertical planes spaced through the beam at approximately one-inch intervals. These planes are designated 1', 2', and 3' in Figure 4.

To study the effect of using traverses of different lengths, determinations of the air content and the number of voids per inch were made with traverses of four different lengths. Four equally spaced traverses were measured on each polished surface. Thus the twelve traverses in each beam could be considered to fall within three vertical or four horizontal planes as shown in Figure 4.

An estimate of the air content of each beam was made using the first four inches of each traverse starting at the right edge and moving the beam to the right. The values for each traverse are given in Table 1. Also given in Table 1 are the values for traverse lengths of six, eight, and ten inches. Table 2 presents similar results for traverses starting at the left edge and moving the beam to the left. Tables 3 and 4 present estimates of the number of voids per inch obtained from the same traverses.

Statistical Analysis

The statistical procedure known as the "analysis of variance" (9) for testing for significant differences among two or more means was followed to determine if the air content and number of voids per inch were dependent upon the position of the traverses with respect to horizontal or vertical planes within the beam. The analysis is based on the fact that if means of subgroups are greatly different, the variance

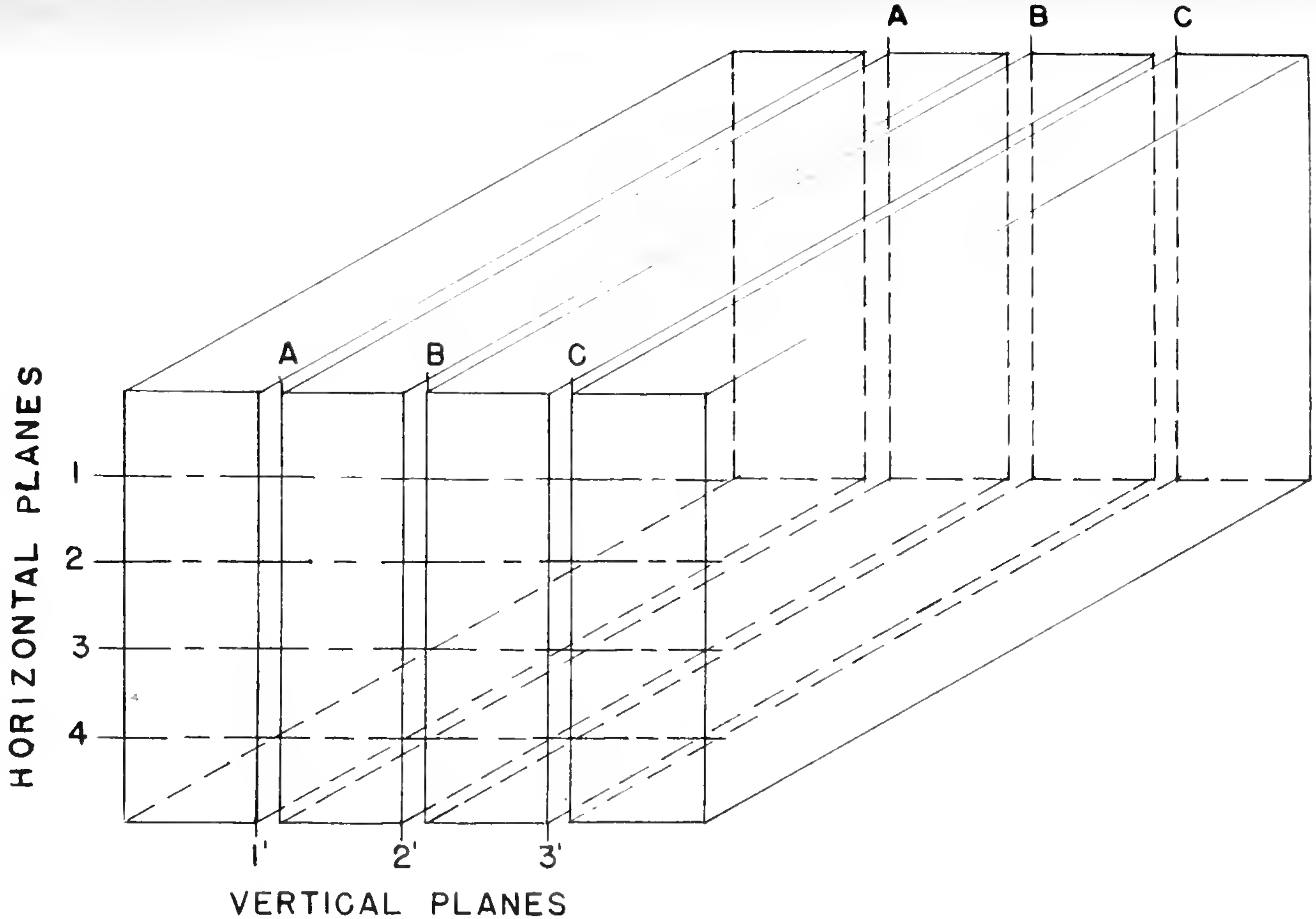


FIG. 4 POSITION OF TRAVERSES WITH RESPECT TO HORIZONTAL AND VERTICAL PLANES IN BEAM

TABLE 1

ARI CONTENT ESTIMATES (PERCENT)--INDIVIDUAL TRAVERSES OF DIFFERENT LENGTHS--RIGHT

Length of Traverses (Inches)	Horizontal Planes	Beam I			Beam II		
		Vertical Planes			Vertical Planes		
		1	2	3	1	2	3
Four	1	5.47	2.58	7.50	6.17	4.03	3.22
	2	0.99	2.50	3.23	2.98	0.74	5.00
	3	0.75	2.99	3.46	3.70	1.27	1.76
	4	2.98	2.99	2.50	5.94	2.75	2.75
Six	1	5.47	4.13	3.65	3.17	2.32	6.25
	2	2.48	0.83	3.81	1.83	4.29	2.64
	3	3.30	2.15	2.32	1.17	3.17	3.82
	4	4.29	3.17	3.65	4.13	3.01	2.00
Eight	1	3.99	2.99	5.59	4.76	3.75	4.23
	2	2.25	3.94	3.26	2.74	2.99	5.90
	3	1.62	2.74	3.39	3.27	2.13	2.13
	4	1.35	2.62	3.91	5.47	3.75	3.75
Ten	1	4.10	2.63	6.64	4.38	3.71	3.66
	2	2.20	3.47	3.45	2.80	3.00	5.47
	3	3.00	2.66	3.29	2.95	1.85	3.90
	4	5.19	2.51	3.86	4.73	3.29	3.68

TABLE 2

AIR CONTENT ESTIMATES (PERCENT)--INDIVIDUAL TRAVERSES OF DIFFERENT LENGTHS--LEFT

Length of Traverses (Inches)	Horizontal Planes	Beam I			Beam II		
		Vertical Planes			Vertical Planes		
		1	2	3	1	2	3
Four	1	[illegible]	3.32	7.73	2.75	3.22	3.70
	2	[illegible]	2.01	5.00	3.23	5.94	6.20
	3	5.71	1.51	3.23	2.50	1.27	5.94
	4	[illegible]	2.01	6.40	5.00	3.94	4.03
Six	1	4.34	2.46	6.35	3.33	3.50	3.97
	2	2.85	3.82	3.82	2.68	4.35	[illegible]
	3	4.53	2.32	3.33	2.84	2.35	5.31
	4	[illegible]	2.15	5.00	3.65	3.50	4.36
Eight	1	1.87	2.23	6.83	3.51	2.74	4.03
	2	[illegible]	3.51	3.51	3.11	3.51	5.47
	3	[illegible]	2.99	3.14	2.74	2.01	4.52
	4	[illegible]	2.13	4.11	5.13	3.26	3.62
Ten	1	[illegible]	2.62	6.64	[illegible]	3.71	3.66
	2	[illegible]	3.47	3.45	2.80	3.06	5.47
	3	3.00	2.66	3.29	1.98	1.85	3.90
	4	[illegible]	2.41	3.86	4.73	3.29	3.66

TABLE 5

ESTIMATES OF NUMBER OF VOIDS PER INCH--INDIVIDUAL TRAVERSES OF DIFFERENT LENGTHS--RIGHT

Length of Traverse (Inches)	Horizontal Planes	Beam I Vertical Planes 1	2	3	Beam II Vertical Planes 1	2	3
Four	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.22	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	5.14	[illegible]	[illegible]
Six	[illegible]	[illegible]	[illegible]	[illegible]	5.06	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Eight	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	7.74	6.12	[illegible]	[illegible]
	4	[illegible]	5.36	[illegible]	5.35	[illegible]	[illegible]
Ten	1	2.70	[illegible]	[illegible]	[illegible]	[illegible]	4.74
	2	2.19	[illegible]	5.62	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.40
	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 4

ESTIMATES OF NUMBER OF [illegible] PER INCH [illegible] INDIVIDUAL TRAVERSES OF DIFFERENT LENGTHS [illegible]

Length of Traverses (Inches)	Horizontal Planes	[illegible] Vertical Planes			[illegible] Vertical Planes		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Four	1	[illegible]	[illegible]	[illegible]	5.00	[illegible]	[illegible]
	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Six	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Eight	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.01
	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ten	1	3.10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	2	[illegible]	4.22	[illegible]	[illegible]	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.90
	4	4.39	[illegible]	4.81	[illegible]	[illegible]	4.47

TABLE 9

ANALYSIS OF VARIANCE--AIR CONTENT (PERCENT)--
LEFT TRAVERSES--VERTICAL PLANES

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F ratio
	Beams	[illegible]	1	[illegible]	[illegible]
	Pl. in Bm.	[illegible].7411	4	[illegible]	[illegible]*
Four	Tr. in Pl.	[illegible]	18	2.5[illegible]	
	Total	[illegible]	23		
	Beams	0.[illegible]	1	[illegible]	[illegible]
	Pl. in Bm.	1[illegible].[illegible]153	4	[illegible]	[illegible]**
Six	Tr. in Pl.	1[illegible].[illegible]042	18	[illegible]	
	Total	[illegible]	23		
	Beams	.0007	1	0.0007	0.00
	Pl. in Bm.	10.9648	4	2.7412	2.32
Eight	Tr. in Pl.	21.[illegible]724	18	1.[illegible]	
	Total	32.[illegible]38[illegible]	23		
	Beams	0.0054	1	.[illegible]	0.00
	Pl. in Bm.	7.4788	4	1.8697	1.67
Ten	Tr. in Pl.	2[illegible].1054	18	1.1170	
	Total	27.5926	23		

$F_{0.95}(4,18) = 2.93$ $F_{0.975}(4,18) = 3.61$

$F_{0.95}(6,16) = 2.74$ $F_{0.975}(6,16) = 3.34$

*Significant at the 5 percent level.

**Significant at the 2.5 percent level.

TABLE 8

ANALYSIS OF VARIANCE--AIR CONTENT (PERCENT)--
LEFT TRAVERSES--HORIZONTAL PLANES

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Four	Beams	[illegible]	1	[illegible]	[illegible]
	Fl. in Br.	[illegible]	6	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Six	Beams	[illegible]	1	[illegible]	[illegible]
	Fl. in Br.	[illegible]	6	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Eight	Beams	[illegible]	1	[illegible]	[illegible]
	Fl. in Br.	[illegible]	6	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Ten	Beams	[illegible]	1	[illegible]	.01
	Fl. in Br.	6.5401	6	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	16	1.3153	
	Total	[illegible]	23		

$F_{0.95}$ (4,1[illegible]) = 2.93 $F_{0.975}$ (4,16) = [illegible]

$F_{0.95}$ (6,16) = 2.74 $F_{0.975}$ (6,16) = [illegible]

significant at either the 5 percent or 2.5 percent significance level for horizontal planes. In Table 7 significance for vertical planes is shown for four and six inch traverses. However, these values of the F ratio are close to those from the standard F ratio tables and as six non-significant cases were found, it was concluded that air content can be determined without regard to the planes within which the traverses may fall.

Tables 9, 10, 11, and 12 present the analysis of variance for the number of voids per inch. The F ratios for significance levels of 5 percent and 2.5 percent are the same as those given above for air content.

Inspection of Tables 10 and 12 shows no significant effect due to horizontal planes. However, significance at the 2.5 percent level is shown for vertical planes in Tables 9 and 11. Since this may have been the result of the operator's difficulty in learning to recognize the smaller voids, another investigation was made later after refinements (such as the use of the sander which was not employed on these initial planes) had been made in the polishing procedure. After refinements in washing the polished surfaces were added along with the use of the electric sander, a further study of the effect of vertical planes was made. The results of this study are presented later in this section.

A 90 percent confidence level for determining the air content of an individual beam within ±0.5 percent of the true air content was selected. Table 13 presents the results of a study of the effect of the length of the individual traverse on the confidence limits for the mean air content. The standard error of the mean is shown to decrease as the length of the traverse is increased with the total number of traverses remaining

TABLE 9

ANALYSIS OF VARIANCE--NUMBER OF V[illegible] [illegible] INCH--
RIGHT TRAVERSES--VERTICAL [illegible]

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Four	Beams	0.7561	1	[illegible]	[illegible]
	Fl. in Br.	41.3169	4	10.3[illegible]	[illegible]
	Tr. in Fl.	32.1445	18	1.78[illegible]	
	Total	74.2175	23		
Six	Beams	0.3800	1	[illegible]	[illegible]
	Fl. in Bm.	[illegible]5.8675	4	[illegible]669	[illegible]
	Tr. in Fl.	2[illegible].3013	16	1.3501	
	Total	50.7488	23		
Eight	Beams	0.3066	1	0.306[illegible]	[illegible]
	Fl. in Bm.	22.7842	[illegible]	[illegible]	[illegible]*
	Tr. in Fl.	14.3965	18	[illegible]	
	Total	37.4867	23		
Ten	Beams	0.3197	1	0.31[illegible]	[illegible]
	Fl. in Bm.	17.8620	4	[illegible]	[illegible]
	Tr. in Fl.	7.3501	18	0.4[illegible]	
	Total	25.5316	23		

$F_{0.95}$ (4,18) = 2.93 $F_{0.975}$ (4,18) = [illegible]

$F_{0.95}$ (6,16) = 2.74 $F_{0.975}$ (6,16) = [illegible]

*Significant at the 2.5 percent level.

TABLE [illegible]

[illegible]

Length of Traverses ([illegible])	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F ratio
Four	Means	[illegible]	[illegible]	[illegible]	[illegible]
	Fl. in Tr.	[illegible]	[illegible]	[illegible]	[illegible]
	Tr. in Fl.	62.0319	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Six	Means	[illegible]	1	[illegible]	[illegible]
	Fl. in Tr.	[illegible]	[illegible]	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Eight	Means	[illegible]	1	[illegible]	[illegible]
	Fl. in Tr.	[illegible]	[illegible]	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Ten	Means	[illegible]	1	[illegible]	[illegible]
	Fl. in Tr.	[illegible]	[illegible]	[illegible]	[illegible]
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		

$F_{0.05}$ [illegible] = [illegible] $\qquad$ $F_{0.01}$ [illegible] = [illegible]

$F_{0.05}$ [illegible] = [illegible] $\qquad$ $F_{0.05}$ [illegible] = [illegible]

TABLE 11

ANALYSIS OF [illegible]

Length of Traverse (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Four	Beams	13.[illegible]11	1	[illegible]	.[illegible]
	Fl. in Br.	[illegible]	[illegible]	[illegible]	.[illegible]
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Six	Beams	[illegible]	1	[illegible]	[illegible]
	Fl. in Br.	[illegible]	[illegible]	[illegible]	.[illegible]
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Eight	Beams	[illegible]	[illegible]	[illegible]	[illegible]
	Fl. in Br.	[illegible]	[illegible]	[illegible]	2.38*
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		
Ten	Beams	[illegible]	1	[illegible]	[illegible]
	Fl. in Br.	[illegible]	4	4.1[illegible]	[illegible]*
	Tr. in Fl.	[illegible]	[illegible]	[illegible]	
	Total	[illegible]	[illegible]		

$F_{0.95}\ (4,18) = [illegible]$ $F_{[illegible]}\ (4,18) = [illegible]$

$F_{0.95}\ (6,18) = [illegible]$ $F_{[illegible]}\ (6,18) = [illegible]$

*Significant at the 2.5 percent level.

TABLE 1[illegible]

ANALYSIS OF VARIANCE--NUMBER OF [illegible]--
LEFT TRAVERSES--HORIZONTAL PLANES

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F ratio
Four	Years	13.2[illegible]	1	13.[illegible]	11.00
	Pl. in Yr.	[illegible]	6	1.[illegible]	[illegible]
	Tr. in Pl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Six	Years	[illegible]	1	[illegible]	5.31
	Pl. in Yr.	[illegible]	6	[illegible].0939	[illegible].73
	Tr. in Pl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Eight	Years	[illegible]	1	[illegible]	[illegible]
	Pl. in Yr.	[illegible]	6	[illegible]	[illegible]
	Tr. in Pl.	[illegible]	16	[illegible]	
	Total	[illegible]	23		
Ten	Years	[illegible]	1	0.0[illegible]	[illegible].13
	Pl. in Yr.	[illegible]	6	0.[illegible]	0.27
	Tr. in Pl.	[illegible].3514	16	1.[illegible]207	
	Total	2[illegible].[illegible]497	23		

$F_{0.95}$ (4,16) = [illegible].93

$F_{0.975}$ (4,16) = [illegible]

$F_{0.95}$ (6,16) = 2.74

$F_{0.975}$ (6,16) = 3.34

[illegible]

Length of Traverse (Inches)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Four	[illegible]	[illegible]	[illegible]	4.19 ± [illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible] ± [illegible]	[illegible]	[illegible]

the same. When the standard error of the mean is computed on the basis of a total of 120 inches of traverses, it is approximately 0.3 for traverses of all lengths.

Very similar results are shown in Table 14 for the number of voids per inch. Tables 13 and 14 show that the total length of the traverses determines the confidence limits for the air content and number of voids per inch rather than the length of an individual traverse. A total traverse length of approximately 140 inches gives the air content of a beam of the type studied within ± 0.5 percent of the true air content and the number of voids per inch within ± 0.5 void per inch. Hence, the measurement of the air content and number of voids per inch of an individual beam may be considered as one long traverse.

To further check on the significance of vertical planes in the determination of the number of voids per inch three additional surfaces (Planes A, B, and C, Figure 4) on each beam were polished using the procedure described under "Preparation of Surface of Concrete Specimen."

Although Tables 13 and 14 show that a total of 140 inches of traverses will give the air content of a beam of the type studied within ± 0.5 percent of the true air content and the number of voids per inch within ± 0.5 void per inch (at the 90 percent confidence level), one hundred inches of traverses on each of two surfaces were selected as standard in order to allow for some increase in variability when examining concrete from other mixes. Therefore, ten traverses of ten inches each were measured on each vertical plane. The data from these planes are presented in Tables 15 and 16.

The results of the analysis of variance are presented in Table 17. The F ratios for vertical planes in beams for both air content and num-

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	

TABLE 15

[illegible] (PERCENT)--[illegible]-INCH TRAVERSES--
[illegible] PLANES--TEN TRAVERSES ON EACH PLANE

Number of Traverse	Beam I Vertical Planes			Beam II Vertical Planes		
	A	B	C	A	B	C
1	[illegible]	2.51	[illegible]	3.98	4.24	2.25
2	[illegible]	[illegible]	[illegible]	4.62	5.89	4.05
3	[illegible]	[illegible]	4.07	2.96	4.39	4.62
4	[illegible]	1.75	[illegible]	3.74	4.81	4.39
5	[illegible]	[illegible]	4.75	3.13	[illegible]	4.43
6	[illegible]	4.21	3.22	5.51	4.53	3.73
7	[illegible]	[illegible]	[illegible]	3.92	5.13	3.16
8	[illegible]	[illegible]	[illegible]	4.55	3.04	5.54
9	[illegible]	[illegible]	6.10	3.06	3.54	3.04
10	[illegible]	4.53	2.75	6.12	2.44	4.13
Average for Plane	[illegible]	3.61	3.70	4.12	4.11	3.73

TABLE 15

[illegible] OF NUMBER OF VOIDS PER INCH--[illegible] VERTICAL PLANES--[illegible] OF EACH PLANE

Number of Traverse	Beam I Vertical Planes			Beam [illegible] Vertical Planes		
	A	B	C	A	B	C
1	[illegible]	[illegible]	3.40	[illegible]	[illegible]	[illegible]
2	[illegible]	4.98	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	4.49	[illegible]	[illegible]	[illegible]
5	[illegible]	3.90	[illegible]	[illegible]	[illegible]	[illegible]
6	4.77	2.22	[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible]	4.56	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	5.77	[illegible]	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	4.63	[illegible]	[illegible]	[illegible]	[illegible]
Average for Plane	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 17

ANALYSIS OF VARIANCE--TEN-INCH [illegible]
[illegible]

Mill Characteristic Measured	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	[illegible]
	Beams	3.[illegible]704	1	[illegible]	[illegible]
[illegible]ir	Fl. in Bm.	2.[illegible]	4	[illegible]	[illegible]
[illegible]	Tr. in Fl.	57.[illegible]	54	1.[illegible]	
	Total	63.5110	59		
	Beams	[illegible]	1	[illegible]	[illegible]
[illegible] of	Fl. in Bm.	[illegible]	4	[illegible]	[illegible]
[illegible] per Inch	Tr. in Fl.	[illegible]	54	[illegible]	
	Total	[illegible]	[illegible]		

ber of voids per inch are less than one. Hence, it may be concluded that vertical planes as well as horizontal planes are not significant in the determination of the air content and the number of voids per inch.

To provide an additional check on the selection of 200 inches as the total length of the traverses within a beam which will give the air content with confidence limits of $\pm$ 0.5 percent and the number of voids per inch with confidence limits of $\pm$ 0.5 void per inch, the planes within each beam were combined in pairs and the confidence limits computed as given in Table 18. The air content and the number of voids per inch are shown to be within these limits. Also, it may be noted that when any two planes are combined the difference from any other combination for the given beam is small.

In order that some comparison might be made between the measurements reported in this study and those made in other laboratories, six concrete specimens were obtained from the Portland Cement Association Laboratory. The results of the measurements made on these specimens are reported in Table 19. One hundred inches of traverse were run on each of two surfaces of each specimen. The results substantiate the procedure developed in this study. Also, the air content measurements check very closely with those obtained in the Portland Cement Association Laboratory.

In conclusion, this investigation shows that the air content and number of voids per inch of a beam of the size and type studied may be determined by the measurement of a totat of 200 inches of traverses within the beam without regard to the position of the traverses with respect to horizontal or vertical planes. The 200 inches of traverses

TABLE 18

[illegible]

Series	Two Plants Compared	Air Content (Percent) (Confidence Limits for the 95% Confidence Level)	[illegible] per Inch (Confidence Limits for the 95% Confidence Level)
	A x B	[illegible].41 ± [illegible]	[illegible] ± [illegible]
I	A x C	[illegible].45 ± [illegible]	[illegible] ± [illegible]
	B x C	[illegible] ± [illegible]	[illegible] ± [illegible]
	A x B	4.11 ± [illegible].41	[illegible] ± [illegible]
II	A x C	[illegible] ± [illegible]	[illegible] ± [illegible]
	B x C	[illegible] ± [illegible]	[illegible] ± [illegible]

TABLE [illegible]

[illegible]

Specimen	Air Content (Percent) Confidence Limits for Specimen-- [illegible] Confidence Level	Number of [illegible] per [illegible] Confidence Limits for Specimen-- [illegible] Confidence Level	[illegible] Value for Air Content ([illegible])
[illegible]	[illegible] ± 0.[illegible]	[illegible] ± [illegible]	[illegible]
2	[illegible] ± [illegible]	[illegible] ± [illegible]	[illegible]
[illegible]	[illegible] ± [illegible]	[illegible] ± [illegible]	[illegible]
[illegible]	[illegible] ± [illegible]	[illegible] ± [illegible]	[illegible]
[illegible]	[illegible] ± [illegible]	[illegible] ± [illegible]	[illegible]
[illegible]	[illegible] ± .57	[illegible] ± [illegible]	[illegible]

give the air content within $\pm$ 0.5 percent of the true air content with 90 percent confidence and the number of voids per inch within $\pm$ 0.5 void per inch with 90 percent confidence.

APPLICATION OF LINEAR TRAVERSE TECHNIQUE TO PAVEMENT CONCRETE

Following the pilot study in which beams fabricated in the Laboratory were used, a study of the variability of the air content and the number of voids per inch within a concrete pavement was made. For this study a section of highway was selected in which two coarse aggregates were used. The portion in which the coarse aggregate was a glacial gravel (source code number 79-1G) showed good field performance. Whereas the portion in which the coarse aggregate was a crushed limestone (source code number 9-1S) was highly deteriorated. Previous studies (33) indicated that the difference in field performance was due to the coarse aggregate. However, in order to check the possibility that some of the difference in durability may have resulted from an accidental difference in air content or some other air-void characteristic, an equal number of cores was taken from the concrete made with each type of aggregate. All the pavement was constructed without the purposeful entrainment of air. Hence, supplemental information was gained on the amount of air accidently entrapped in concrete pavements.

Pavement Construction

The cores for this study were taken from a section of Indiana State Road 43 starting at the beginning of the concrete pavement in Brookston, Indiana, and proceeding north. The contract for the construction of this pavement was awarded June 21, 1929, and completed June 14, 1930. The pavement is an eighteen-foot wide 9-7-9 section with a longitudinal 3/4-inch round bar placed six inches from the outside edge on each side. The mix proportion was 1:2:3 by weight with a cement factor of 1.72

barrels per cubic yard. A water-cement ratio of 0.50 by weight was used. The maximum size aggregate was 2 $\frac{1}{4}$ inches.

Starting at the beginning of the concrete pavement in Brookston two cores were taken on a line transverse to the centerline every 0.2 mile for a distance of 1.8 miles. Thus, a total of twenty cores (designated S11 to S120) were obtained from pavement in which coarse aggregate 9-1S was used. Starting at a point 2.2 miles from the beginning of the concrete pavement in Brookston two cores were taken every 0.3 mile from pavement in which coarse aggregate 79-1G was used for a total of twenty cores (designated G11 to G120).

Two parallel surfaces from each core were polished following the procedure described in the preceding section. Then measurements of the air content and number of voids per inch were made using a total of one hundred inches of traverse on each surface. The results of these measurements are presented in Tables 20 and 21.

Analysis of Data and Summary of Results

Confidence limits for air content and number of voids per inch are presented in Table 22 for six gravel cores and six stone cores. The volume of a core is of the same order of magnitude as the volume of a concrete beam examined in the pilot study. The results agree substantially with the conclusion of the preceding section that two hundred inches of traverses will give the air content within $\pm$ 0.5 percent of the true value at the 90 percent confidence level.

The pavement constructed with crushed limestone showed an average air content of 2.0 percent (average of values for air content in Table 20). The pavement constructed with glacial gravel showed an average

Transverse	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 22

CONFIDENCE LIMITS FOR AIR CONTENT AND NUMBER OF VOIDS PER INCH--PAVEMENT CORES--TWO HUNDRED INCHES OF TRAVERSES ON TWO PLANES

Pavement Core	Air Content	Number of Voids per Inch
	Confidence Limits for Core (90% Confidence Level)	Confidence Limits for Core (90% Confidence Level)
S11	[illegible]	1.02 ± 0.13
S12	[illegible]	1.21 ± 0.11
S13	[illegible] ± 0.21	0.60 ± 0.07
S14	[illegible]	0.48 ± 0.06
S15	[illegible]	0.75 ± 0.11
S16	[illegible]	0.86 ± 0.11
G11	[illegible] ± 0.43	1.06 ± 0.13
G12	2.30 ± [illegible]	1.12 ± 0.13
G13	[illegible]	1.16 ± 0.12
G14	1.59 ± 0.29	0.96 ± 0.12
G15	1.91 ± [illegible]	0.83 ± 0.12
G16	[illegible]	0.80 ± 0.11

air content of 1.7 percent (average of values for air content in Table 21). For both sections of pavement the average value for the number of voids per inch was 0.8 void per inch.

The analysis of variance for air content is presented in Table 23; while the analysis of variance for number of voids per inch is presented in Table 26. In these tables it is shown that neither the air content nor the number of voids per inch for the pavement constructed with crushed limestone is significantly different from the corresponding value for the pavement constructed with glacial gravel for the coarse aggregate. Hence, it may be concluded that the differences in durability were not due to differences in the entrapped air.

Use of Core Data to Develop Sampling Plan for Concrete Pavements

In the sampling of concrete pavements it is desired to study the variability of the air content and number of voids per inch of a section of highway and not just a particular core. For this purpose a surface which represents an estimate of these variables based on a traverse length of one hundred inches was used as the smallest unit for sampling. On the basis of the study in the preceding section this length of traverse is believed to be fair and satisfactory for a given surface.

Beginning with surfaces as the smallest unit the sampling of a section of pavement may be considered a three-stage sampling problem in which the sources of variation are: (a) surfaces within cores, (b) cores within transverse lines, and (c) transverse lines within the section. Each of these sources of variation has its own particular variance. By study of the relative magnitudes of these components of the total variance a sampling scheme was evolved whereby the air content or

TABLE [illegible]

ANALYSIS OF [illegible] - AIR CONTENT (PERCENT)--CONCRETE PAVEMENT

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.01}$	Significance
Aggregates	1	[illegible]	[illegible]	[illegible]	[illegible]	NS
Transverse Lines within Stone Agg.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Transverse Lines within Gravel Agg.	9	[illegible]	[illegible]			
Transverse Lines within Agg. (Total)	1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	NS
Cores within Stone Trans. Lines	1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	NS
Cores within Gravel Tran. Lines	1[illegible]	4.61	[illegible]			
Cores within Trans. Lines (Total)	20	[illegible]	[illegible]	[illegible]	1.34	[illegible]
Surfaces within Stone Cores	20	[illegible]	0.12	1.09	2.12	NS
Surfaces within Gravel Cores	20	[illegible]	0.11			
Surface within Cores (Total)	4[illegible]	4.73	0.12			

*Significant at the 1 percent level.

the number of voids per inch may be determined within a given confidence interval.

In this study the average cost of obtaining a core was $10.00. To this cost was added the cost of sawing which was estimated to be $1.00 per core. Hence, the total cost per core was approximately $11.00. The time required to prepare and observe a surface was approximately four hours. From this the cost per surface was estimated to be $5.00. These values were used to set up tables for determining the minimum cost to obtain the air content or number of voids per inch within a given confidence interval.

In the following analysis the procedures recommended in Chapter 10 of Sampling Techniques by W. G. Cochran (8) were used.

Air Content

To study the variability of the air content of the concrete pavement investigated, an analysis of variance was made in which the sources of variation are aggregates, transverse lines, cores, and surfaces. The analysis of variance is presented in Table 23.

A study of Table 23 shows that the various stages of variability do not need to be treated differently for stone cores than for gravel cores since the F ratios are not significant. Therefore, the mean squares for stone and gravel may be pooled. This results in a mean square of 0.67 for transverse lines and a mean square of 0.40 for cores. Since $0.67/0.40 = 1.68$ is not significant and cores are significantly variable beyond the surface to surface variation, it may be concluded that the stratification of the pavement into transverse lines is not necessary. Hence, the sampling problem consists of regarding the stretch

of concrete pavement as a universe with the selection of a random sample of cores from the stretch. From each core, surfaces are examined in the sedond stage of sampling.

Considering the problem as a two-stage sampling problem the components of the analysis of variance are presented in Table 24.

TABLE 24

COMPONENTS OF VARIANCE--TWO-STAGE SAMPLING PROBLEM

Source of Variation	Degrees of Freedom	Mean Square	EMS (Expected Value of Mean Square)
Cores	$n - 1$	0.40	$\sigma_s^2 + m\sigma_c^2$
Surfaces Within Cores	$n(m - 1)$	0.12	σ_s^2

$\sigma_s^2 =$ variance of surfaces within cores,

$\sigma_c^2 =$ variance of core means in universe,

$n =$ number of cores examined, and

$m =$ number of surfaces examined per core.

If n cores are selected at random from a universe stretch of pavement and m surfaces per core are observed, $x_{ij} =$ air content from surface j of core i with $j = 1, 2, \ldots, m$, and $i = 1, 2, \ldots, n$.

Then the best estimate of the universe mean is:

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij}}{mn}$$

And the variance of $\bar{\bar{X}}$ is:

$$s_{\bar{\bar{X}}}^2 = \frac{\sigma_s^2 + m\sigma_c^2}{mn} = \frac{\sigma_s^2}{mn} + \frac{\sigma_c^2}{n}$$

From the analysis of variance, Table 24, $\sigma_s^2 + m\,\sigma_c^2 = 0.40$ and $\sigma_s^2 = 0.12$. Thus, with $m = 2$, $\sigma_c^2 = 0.14$ and:

$$s_{\bar{\bar{X}}}^2 = \frac{0.12 + 0.14\ m}{mn}$$

The $(1 - \alpha)$ percent confidence limits for the universe mean are $\bar{\bar{X}} \pm t_{1-\alpha/2}\, s_{\bar{\bar{X}}}$ where t is on the degrees of freedom for the core mean square, $n - 1$.

Table 25a presents the half lengths of the confidence intervals around $\bar{\bar{X}}$ for a confidence level of 90 percent. Also included in Table 25a are cost estimates based on the estimated unit costs of \$5.00 per surface and \$11.00 per core. Similar information is given in Tables 25b and 25c for confidence levels of 95 percent and 97.5 percent, respectively.

These tables may be used to obtain the estimated cost of sampling a pavement to obtain the air content within a given confidence interval. For example: To obtain the air content of a stretch of pavement within - 0.30 percent of the true air content at the 95 percent confidence level, Table 25b shows that one surface from each of 14 cores should be observed. The cost would be \$224. If two surfaces are observed from each core, 12 cores are needed at a cost of \$252.

Number of Voids per Inch

A Procedure similar to that used for air content was followed in studying the variability of the number of voids per inch in a stretch of concrete pavement. The analysis of variance is presented in Table 26.

TABLE 25a

VALUES FOR COMPUTING CONFIDENCE LIMITS AND COST OF SAMPLING--AIR CONTENT (PERCENT)--90 PERCENT CONFIDENCE LEVEL

Number of Cores (n)	$t_{0.90}$	Number of Surfaces per Core (s)								
		1			2			3		
		$S_{\bar{\bar{X}}}$	$\pm tS_{\bar{\bar{X}}}$	Cost $	$S_{\bar{\bar{X}}}$	$\pm tS_{\bar{\bar{X}}}$	Cost $	$S_{\bar{\bar{X}}}$	$\pm tS_{\bar{\bar{X}}}$	Cost $
4	2.35	0.25	0.59	64	0.22	0.52	84	0.21	0.49	104
6	2.01	0.21	0.42	96	0.18	0.36	126	0.17	0.34	156
8	1.89	0.18	0.34	128	0.16	0.30	168	0.15	0.28	208
10	1.83	0.16	0.29	160	0.14	0.26	210	0.13	0.24	260
12	1.80	.15	0.27	192	0.13	0.23	252	0.12	0.22	312
14	1.77	.14	0.25	224	0.12	0.21	294	0.11	0.19	364
16	1.75	0.13	0.23	256	0.11	0.19	336	0.11	0.19	416
18	1.74	0.12	0.21	288	0.11	0.19	378	0.10	0.17	468
20	1.73	0.11	0.19	320	0.10	0.17	420	0.09	0.16	[illegible]

Note: Cost of one core including sawing = $11.00

Cost per surface = $5.00

TABLE 25b

VALUES FOR COMPUTING CONFIDENCE LIMITS AND COST OF SAMPLING--
AIR CONTENT (PERCENT)--95 PERCENT CONFIDENCE LEVEL

Number of Cores (n)	$t_{.05}$	Number of Surfaces per Core (m)								
		1			2			3		
		$S_{\bar{X}}$	$\pm tS_{\bar{X}}$	Cost $	$S_{\bar{X}}$	$\pm tS_{\bar{X}}$	Cost $	$S_{\bar{X}}$	$\pm tS_{\bar{X}}$	Cost $
4	3.18	0.25	0.80	64	0.22	0.70	[illegible]	0.21	0.67	[illegible]
6	2.57	0.21	0.54	[illegible]	0.18	0.46	126	0.17	0.44	156
8	2.36	0.18	0.42	128	0.16	0.38	168	0.15	[illegible]	208
10	2.26	0.15	0.36	160	0.14	0.32	210	0.13	[illegible]	260
12	2.20	0.15	0.33	192	0.13	0.29	252	0.12	[illegible]	312
14	2.16	0.14	0.30	224	0.12	0.26	294	0.11	[illegible]	364
16	2.13	0.13	0.28	256	0.11	[illegible]	336	[illegible]	[illegible]	[illegible]
18	2.11	0.12	0.25	288	0.11	0.23	378	0.10	0.21	[illegible]
20	[illegible]	0.11	0.23	320	0.10	0.21	420	[illegible]	[illegible]	520

Note: Cost of one core including sawing = $11.00.

Cost per surface = $5.00.

TABLE 25

VALUES FOR COMPUTING CONFIDENCE LIMITS AND COST OF SAMPLING--
AIR CONTENT (PERCENT)--97.5 PERCENT CONFIDENCE LEVEL

Number of Cores (n)	$t_{0.975}$	Number of Surfaces per Core (m)								
		1			2			3		
		$S_{\bar{x}}$	$\pm tS_{\bar{x}}$	Cost $	$S_{\bar{x}}$	$\pm tS_{\bar{x}}$	Cost $	$S_{\bar{x}}$	$\pm tS_{\bar{x}}$	Cost $
4	[illegible].18	[illegible]	[illegible]	[illegible]	[illegible].22	[illegible]	84	0.21	0.[illegible]7	104
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].55	126	0.17	0.44	156
8	[illegible]	[illegible].18	[illegible].41	[illegible]	[illegible]	[illegible]	168	0.15	0.4[illegible]	208
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	210	[illegible].13	0.35	260
12	[illegible]	[illegible].15	[illegible]	[illegible]	0.13	0.34	252	[illegible].12	[illegible].31	312
14	[illegible]	0.14	0.[illegible]	224	0.1[illegible]	0.30	294	0.11	0.[illegible]	[illegible]
16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].11	0.2[illegible]	336	[illegible].11	0.27	416
18	[illegible]	[illegible].12	[illegible]	[illegible]	[illegible]	[illegible]	378	0.10	[illegible]	[illegible]
[illegible]	[illegible]	0.11	[illegible]	[illegible]	[illegible].10	[illegible]	420	0.[illegible]	[illegible]	520

Note: Cost of one core including sawing = $11.00.

Cost per surface = $5.00.

TABLE- [illegible]

ANALYSIS OF VARIANCE--NUMBER OF VOIDS PER INCH--CONCRETE PAVEMENT

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F [illegible]	F .05	Significance
Aggregates	1	[illegible]	[illegible]	[illegible]	4.4[illegible]	NS
Transverse Lines within Stone Agg.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	NS
Transverse Lines within Gravel Agg.	[illegible]	[illegible]	[illegible]			
Transverse Lines within Agg. (Total)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cores within Stone Transverse Lines	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cores within Gravel Transverse Lines	[illegible]	[illegible]	[illegible]			
Cores within Trans. Lines (Total)	[illegible]	[illegible]	0.[illegible]	[illegible]	[illegible]	[illegible]
Surfaces within Stone Cores	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	NS
Surfaces within Gravel Cores	[illegible]	[illegible]	[illegible]			
Surfaces within Cores (Total)	[illegible]	[illegible]	[illegible]			

*Significant at the 5 percent level.

**Significant at the [illegible] percent level.

Again homogeneity of variance between stone and gravel cores prevails throughout. Hence, the mean squares for stone and gravel cores may be pooled.

Since transverse lines are significant, there appears to be a gain through sampling in transverse lines. Thus the sampling process becomes a three-stage sampling problem. The components of the analysis of variance are presented in Table 27.

TABLE 27

COMPONENTS OF VARIANCE--THREE-STAGE SAMPLING PROBLEM

Source of Variation	Degrees of Freedom	Mean Square	EMS (Expected Value of Mean Square)
Transverse Lines	$k - 1$	0.142	$\sigma_s^2 + m\sigma_c^2 + np\sigma_t^2$
Cores Within Transverse Lines	$k(p - 1)$	0.029	$\sigma_s^2 + m\sigma_c^2$
Surfaces Within Cores	$kp(m - 1)$	0.014	σ_s^2

σ_s^2 = variance of surfaces within cores,

σ_c^2 = variance of core means within transverse lines,

σ_t^2 = variance of transverse line means in universe,

k = number of transverse lines,

p = number of cores per transverse line, and

m = number of surfaces examined per core.

For $i = 1, 2, \ldots, k$, $j = 1, 2, \ldots, p$, and $s = 1, 2, \ldots, m$; x_{ijs} represents the value for the number of voids per inch from one surface and the sample mean is:

$$\bar{\bar{\bar{X}}} = \frac{\sum_{i=1}^{k} \sum_{j=1}^{p} \sum_{z=1}^{m} x_{ijz}}{kpm}$$

with the variance of $\bar{\bar{\bar{X}}}$:

$$S_{\bar{\bar{\bar{X}}}}^2 = \frac{\sigma_s^2 + m\sigma_c^2 + mp\,\sigma_t^2}{kpm}$$

From the analysis of variance, Table 27, $\sigma_s^2 = 0.014$, $\sigma_s^2 + m\sigma_c^2 = 0.029$, and $\sigma_s^2 + m\sigma_c^2 + mp\sigma_t^2 = 0.142$. With $m = 2$ and $p = 2$, $\sigma_c^2 = 0.008$ and $\sigma_t^2 = 0.028$. The variance of $\bar{\bar{\bar{X}}}$ becomes:

$$S_{\bar{\bar{\bar{X}}}}^2 = \frac{0.014}{kpm} + \frac{0.008}{kp} + \frac{0.028}{k}$$

The $(1 - \alpha)$ percent confidence limits for the universe mean are $\bar{\bar{\bar{X}}} \pm t_{1-\alpha/2} S_{\bar{\bar{\bar{X}}}}$ where t is on the degrees of freedom for the transverse line mean square, $k - 1$.

Tables 28a and 28b present the values for computing the confidence limits for a confidence level of 95 percent. Also presented in these tables are the costs of sampling for the various combinations of k, p, and m. Again the costs are based on unit costs of $11.00 per core and $5.00 per surface.

Summary

A study of Tables 28a and 28b shows that it is necessary to take a rather large number of transverse lines in preference to several cores in a transverse line or several surfaces per core. With $p = 1$, k takes the place of n as used in the air content determination when a study of the number of voids per inch is made. Then the variance for the number

TABLE [illegible]

VALUES FOR COMPUTING CONFIDENCE LIMITS AND COST OF SAMPLING--NUMBER OF VOIDS PER INCH
[illegible] PERCENT CONFIDENCE LEVEL)--[illegible] CORE PER TRANSVERSE LINE

Number of Transverse Lines (k)	[illegible]	1			[illegible]			[illegible]		
		CM [illegible]	± [illegible]	[illegible] $	CM [illegible]	± [illegible]	Cost $	CM [illegible]	± CLM [illegible]	Cost $
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Note: Cost of [illegible] = $[illegible].
Cost per surface = $[illegible].

TABLE [illegible]

VALUES FOR COMPUTING CONFIDENCE LIMITS AND COST OF SAMPLING--NUMBER OF VOIDS PER INCH
([illegible] PERCENT CONFIDENCE LEVEL)--[illegible] COLS PER TRANSVERSE LINE

Number of Transverse Lines	[illegible]	[illegible]								
		$\sigma_{\bar{x}}$	± [illegible]	[illegible]	[illegible]	± [illegible]	[illegible]	[illegible]	± [illegible]	Cost
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]			[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.09	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Note: Cost of one [illegible] sawing = [illegible].

Cost per surface = [illegible].

of voids per inch becomes:

$$S^2_{\bar{\bar{X}}} = \frac{0.014 + 0.036m}{km}$$

Thus, examination of Tables 25a, 25b, 25c, 28a, and 28b suggests simple random sampling along the stretch of pavement with measurements on one surface per core. From the n cores examined the air content is

$$\bar{\bar{X}} \pm t\sqrt{\frac{0.26}{n}} \; ;$$

and the number of voids per inch is

$$\bar{\bar{X}} \pm t\sqrt{\frac{0.05}{n}} \; ;$$

with t having n - 1 degrees of freedom.

A STUDY OF THE CORRELATION BETWEEN AIR-VOID CHARACTERISTICS AND THE DURABILITY OF LABORATORY CONCRETE BEAMS

Concrete beams which were fabricated for use in another investigation conducted in the concrete laboratory of the Joint Highway Research Project were selected for use in this study. These beams were chosen because of the unexplained differences in durability between beams from the same mix and between mixes made from the same materials under similar conditions.

Materials

All beams used in this study were made with crushed stone coarse aggregates. Data on these aggregates are presented in Table 29. The six coarse aggregates from the sources in the Kokomo limestone formation have poor durability records. The source from the Liston Creek formation has a good field performance record.

Type I portland cement from a single clinker batch (Cement 312) was used in all mixes. The chemical composition and results of physical tests of the cement as reported by the manufacturer are shown in Table 30.

The fine aggregate used in all mixes was obtained from a river terrace deposit of glacial origin and is known in the laboratory as source 79-1. This fine aggregate has been used in the Joint Highway Research Project concreted laboratory for years as a standard material and is considered to be a durable material in laboratory freeze-thaw weathering. The bulk saturated surface dry specific gravity of the fine aggregate was 2.65 and the fineness modulus for the gradation was 3.10. The absorption was 1.65 percent by weight.

Darex and neutralized vinsol resin solution were used as air-

TABLE 29

COARSE AGGREGATES

Aggregate Designation	Aggregate Source Number	Laboratory Sample Number	Description	Geological Origin	Bulk Sp.Gr.	True Sp.Gr.	Absorption After Evacuation and Saturation Percent by Wt.	Degree of Saturation Percent
A_1	9-2S	2033-A	Upper 25 feet--Ledges 1, 2, 3, 4	Silurian (Kokomo Formation)	2.63*	1-2.72 2-2.89 3-2.86 4-2.86	2.69	1-76 2-88 3-96 4-100
A_2	9-2S	2033-B	Lower 21 feet--Ledges 5, 6, 7	Silurian (Kokomo Formation)	2.53	5-2.86 6-2.87 7-2.86	4.66	5-100 6-94 7-100
A_3	9-2S	2033-C	Stockpile Sample	Silburian (Kokomo Formation)	2.57		3.95	
A_4	9-1S	2034	Ledge sample	Silurian (Kokomo Formation)	2.45	2.86	5.85	100
A_5	9-5S	2032-A	Upper 24 feet--Ledge 1, 2, 3, 4	Silurian (Kokomo Formation)	2.59	2.85	3.19	88
A_6	9-5S	2032-B	Lower 24 feet--Ledges 5, 6, 7	Silurian (Kokomo Formation)	2.46	2.85	5.65	100
A_7	1-1S	2037	Stockpile Sample	Silurian (Liston Creek Formation)	2.68	2.85	1.98	90

*Values given are for combined sample unless individual ledges are indicated.

TABLE [illegible]

CHEMICAL ANALYSIS AND RESULTS OF PHYSICAL TESTS ON CEMENT

Chemical Analysis	Percent [illegible]	Physical Tests	
SiO_2	[illegible].06	Fineness, pass #200, per cent	[illegible]
Al_2O_3	5.45	S. A. Wagner, sq. cm. per gm.	[illegible]
Fe_2O_3	2.[illegible]	S. A. Blaine	[illegible]
CaO	[illegible]	Set Initial, hr: min.	[illegible]
MgO	0.96	Final, hr: min.	[illegible]
SO_3	[illegible]	Normal Consistency	[illegible]
Loss of Ignition	0.74	Percent Water Cubes	[illegible]
Free CaO	0.96	Flow	[illegible]
Compound Composition		Air Content of Mortar, Per cent	[illegible]
C_3S	[illegible]	[illegible]	[illegible]
C_2S	[illegible]	[illegible]	
C_3A	[illegible]	[illegible]	
C_4AF	[illegible]	[illegible] Days	[illegible]
$CaSO_4$	[illegible]	[illegible]	[illegible]
Insoluble [illegible]	[illegible]	[illegible]	[illegible]
Soda	[illegible]	Compressive Strength, [illegible]	
Potash	[illegible]	1 Day	[illegible]
Total alkali	[illegible]	3 Days	[illegible]
		7 Days	[illegible]
		28 Days	[illegible]

entraining agents.

Concrete Mixes

All coarse aggregates were vacuum saturated before being incorporated in concrete mixes designed for a water-cement ratio of 0.46 by weight, a cement factor of six bags per cubic yard, and a slump of three to four inches. The maximum size of aggregate was one inch. The air content of the fresh concrete was measured gravimetrically according to A.S.T.M. Designation: C:138-44, (1) except that a 0.1 cubic foot measure was used because of the small size of the concrete mixes. The concrete used for making the air content determination was discarded. Three concrete beams, 3 x 4 x 16 inches, were made from each mix. Curing was by immersion in water for 13 days following removal of the specimens from molds one day after casting.

Freezing and Thawing of Beams

Automatic freezing and thawing equipment was used for the freezing and thawing of the beams. R. D. Walker (27) has described this equipment in the following manner.

> Essentially, the equipment consists of two compartments with a capacity of 25 beams in a freezing chamber and a thaw water storage tank. The refrigeration coils are around the perimeter of the two compartments. Uniform air temperature is obtained in the freezing chamber by two fans mounted above the specimens. Immersion heaters keep the water in the storage tank at a constant 40°F. temperature.
>
> The air temperature was reduced to 0° F. in about one hour of the freezing cycle, and within 2-1/2 hours the centers of the beams also reached 0° F. At this time, the thaw water was circulated, and the ambient temperature quickly rose to 40° F. The centers of the specimens reached 40° F. within 30 minutes. After 35 minutes had elapsed, the water was pumped out during a 6 minute period, and then the freezing cycle began again. Approximately seven cycles per day were obtained.

Periodic tests of the dynamic modulus of elasticity were made to

measure the amount of deterioration. In most cases freezing and thawing was continued until a decrease in dynamic E to 50 percent of the original value occurred or until 800 cycles of freezing and thawing were completed. For use in studying the air-void characteristics two beams were selected from each mix--the most durable and the least durable. A total of 38 beams from 19 mixes was studied.

Measurement of Deterioration

Durability factors were used to express the durability of each beam selected for measurement of the air-void characteristics. Four different durability factors were computed for each beam.

Durability factors No. 1 and 2 were calculated following the procedure given in A.S.T.M. Designation: C290-52T (1) in which

$$DF = \frac{PN}{M}$$

where:

DF = durability factor of the test specimen;

P = relative dynamic modulus of elasticity at N cycles, percent;

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less; and

M = specified number of cycles at which the exposure is to be terminated.

Durability factor No. 1 was computed with M = 200 cycles while durability factor No. 2 was computed with M = 300 cycles.

Durability factors No. 3 and 4 were computed following the proce-

dure suggested by Stanton Walker (28), the method for which is shown graphically in Figure 5. This durability factor may be defined as the area under the curve to the left of the nth cycle and above the 50 percent dynamic E line, expressed as a percentage of the total area to the left of the nth cycle and above the 50 percent dynamic E line. For durability factor No. 3, n = 200 cycles and for No. 4, n = 300 cycles.

Table 31 gives the values of the four different durability factors which were computed for each of the 38 beams included in this investigation.

Formulas Used for the Computation of Air-Void Characteristics

The air-void characteristics which were investigated for correlation with durability were:

A = air content, total volume of voids per unit volume of concrete, percent,

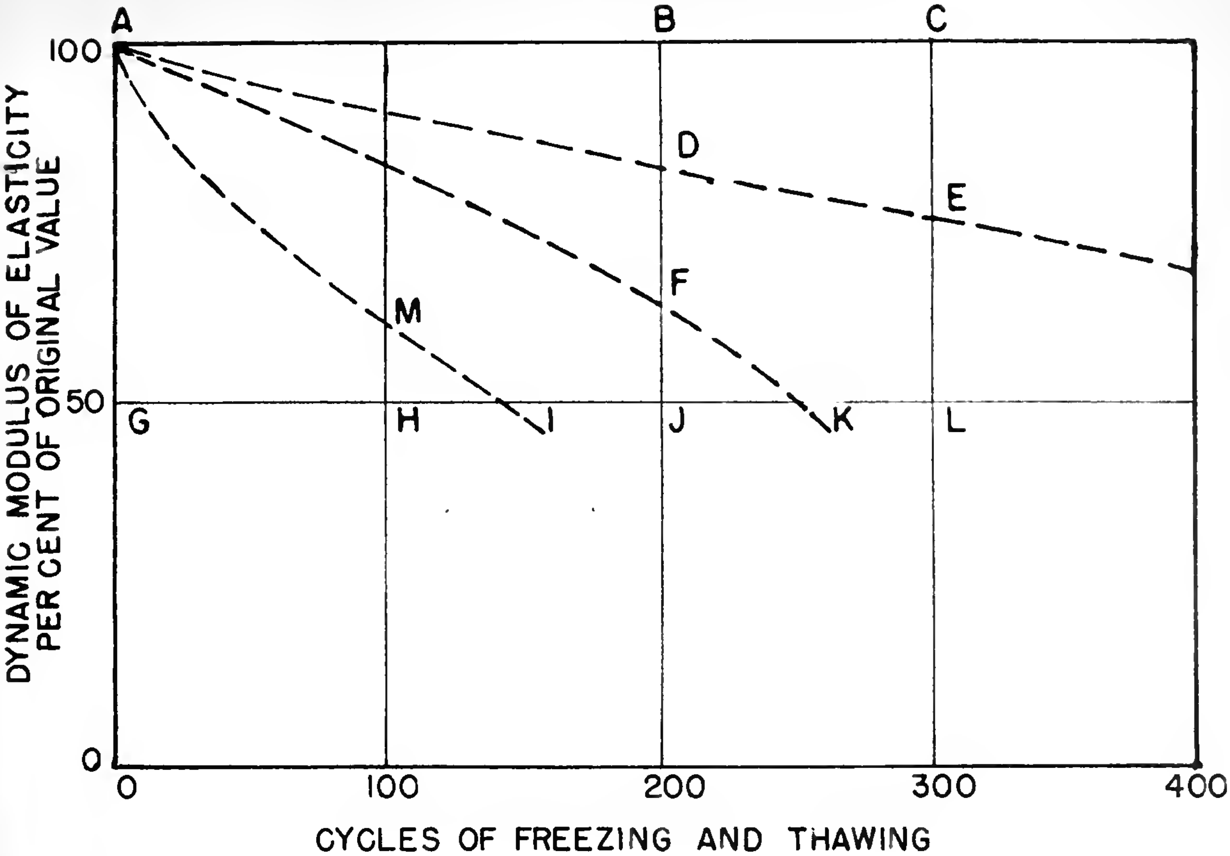
n = number of voids intersected per unit length of traverse, voids per inch,

α = the specific surface of the air voids, the surface area of the voids per unit volume of air, square inches per cubic inch,

N = number of hypothetical spheres having radius r_h that would equal the actual air content of the concrete, voids per cubic inch, and

L = spacing factor, distance from void boundary to outer boundary of sphere of influence, inches.

Two of the characteristics, A and n, were measured directly with



CURVE	DURABILITY FACTORS	
	NO. 3 (AT 200 ∿)	NO. 4 (AT 300 ∿)
AMI	$\frac{AMIG}{ABJG}$	$\frac{AMIG}{ACLG}$
AFK	$\frac{AFJG}{ABJG}$	$\frac{AFKG}{ACLG}$
ADE	$\frac{ADJG}{ABJG}$	$\frac{ADELG}{ACLG}$

FIG. 5 COMPUTATION OF METHOD FOR DURABILITY FACTORS NO. 3 & 4. AFTER WALKER (28)

TABLE [illegible]

DURABILITY OF LABORATORY CONCRETE BEAMS

Aggregate Designation	Laboratory Mix Designation	Air Content as Measured on Fresh Concrete	Beam Designation	Durability Factors [illegible]			
				1	[illegible]	3	4
A_1	[illegible]-AE	[illegible]	A11	10[illegible]	[illegible]	[illegible]	100
			A1[illegible]	[illegible]	[illegible]	[illegible]	100
	[illegible]	[illegible]	A31	[illegible]4	[illegible]	[illegible]	[illegible]
			[illegible]	2[illegible]	[illegible]	[illegible]	2[illegible]
A_2	[illegible]-B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	4.7	[illegible]21	[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]	[illegible]	[illegible]		[illegible]
	3[illegible]-7[illegible]	[illegible]	[illegible]21	[illegible]	[illegible]	[illegible]	17
			[illegible]	16	[illegible]	[illegible]	15
A_3	3[illegible]-31	[illegible]	3[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			313	[illegible]	[illegible]	[illegible]	[illegible]
	3[illegible]-3[illegible]	[illegible].8	321	[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]32	90	80	87	[illegible]
A_4	4[illegible]-[illegible]	[illegible]	42[illegible]	51	54	[illegible]	42
			423	61	48	55	62
	[illegible]4-3	3.5	432	4[illegible]	5[illegible]	60	40
			433	100	102	100	100
	34-4	3.3	441	1[illegible]	1[illegible]	19	1[illegible]
			442	35	2[illegible]	38	25
A_5	SA-1	3.4	SA11	78	55	80	66
			SA13	99	100	99	100
	SA-2	4.7	SA21	94	93	94	92
			SA23	98	97	95	95
	SA-3	3.7	SA32	97	67	90	78
			SA33	95	95	92	92

TABLE 31--Continued

Aggregate Designation	Laboratory Mix Designation	Air Content as Measured on Fresh Concrete	Beam Designation	Durability Factors			
				1	2	3	4
A_5	SB-1	[illegible]	SB11	100	100	100	100
			SB12	99	90	97	92
	SB-2	6.2	SB21	74	[illegible]	[illegible]	60
			SB22	[illegible]	[illegible]	63	57
	SB-3	3.[illegible]	SB31	50	33	57	38
			SB32	36	21	38	25
	SB-4	4.9	SB41	48	32	42	41
			SB42	55	23	45	30
	SB-5	7.5	SB52	97	[illegible]	97	57
			SB53	[illegible]	[illegible]	52	35
A_7	ST-1	[illegible]	T11	101	104	100	100
			T12	[illegible]	104	100	100

the linear traverse integrator. The remaining three were computed from these two measurements with the paste content being introduced in the computation of the spacing factor.

The equations that were used for the computation of α, N, and L were presented along with their development in the paper "The Air Requirement of Frost-Resistant Concrete" by T. C. Powers (19) and a discussion of the same paper by T. F. Willis (31).

T. F. Willis (31) showed that regardless of the size distribution of the voids the true specific surface of the voids is given by the equation: $\alpha = \frac{4n}{A}$.

N and L are obtained by assuming that the voids are equal-size spheres with each sphere having the same specific surface as the measured specific surface. Powers (19) and Willis (31) show that the radius r_h of this hypothetical sphere is equal to $\frac{3}{\alpha}$ or $\frac{3\bar{I}}{4}$ where:

$\bar{I}$ = the arithmetic mean of the measured chord intercepts.

The hypothetical number of spheres, N, may be computed from the following formula:

$$N = \frac{A}{\frac{4\pi r_h^3}{3}} = \frac{A}{\frac{4\pi}{3}\left(\frac{3}{\alpha}\right)^3} = \frac{A\alpha^3}{36\pi}$$

Thus the computation of N and L is based on a hypothetical system of uniform-sized spheres having the same volume of air pet unit volume of concrete and the same specific surface as the system of random sized voids for which A and n are measured.

To compute the void spacing factor for the hypothetical void system, each sphere is considered to be at the center of a cube with the sum of the volumes of all such cubes and the enclosed spheres equaling

the combined air and paste content of the concrete. The "sphere of influence" of each void is the radius of the sphere circumscribing the hypothetical cube. The spheres will overlap except at the corners of the cubes. The radius of the sphere of influence is equal to one-half the diagonal of the cube.

The volume of a single hypothetical cube is $\frac{p + A}{N}$ where p = paste content; sum of volumes of water and cement per unit volume of concrete. Hence, the length of one edge of the hypothetical cube is $\left(\frac{p + A}{N}\right)^{1/3}$.

And,

$$r_m = \frac{\sqrt{3}}{2} \left(\frac{p + A}{N}\right)^{1/3}$$

where r_m = radius of circumscribed sphere, the "sphere of influence."

The spacing factor L is equal to the difference between the radius of the sphere of influence r_m and the radius of the sphere r_h; that is, $L = r_m - r_h$.

Measurement of A and n

Four operators were used to make the measurements of A and n on the 38 beams for which durability factors were determined. From a study of the data on surfaces which had been measured by the writer it was concluded that the maximum difference in the value obtained for A by measurements on different surfaces from the same beam could be estimated to be ±0.5 percent. In order to minimize the effect of using more than one operator, each operator was required to study surfaces measured by the writer until he was able to obtain values within ±0.5 percent and ±0.5 void per inch of the values obtained for A and n, respectively, by the writer for the same surface. Then a particular surface was selected

as a standard and at the beginning and at definite intervals measurements were repeated on this surface by each operator as a control on his work.

To further reduce the effect of using different operators, one operator observed one surface while another operator observed the other surface from the same beam. Also, the beams from a particular mix were observed by the same two operators with each making the observations on one surface of each beam.

Values of A and n for the 38 beams observed in this study are tabulated in Table 32.

Computation of Air-Void Characteristics

Included in Table 32 are the computed values for α, N, and L. Beam A22 is used as a typical example in the computation of the air-void characteristics which follows:

$$A = 4.9 \qquad n = 9.1 \qquad p = 0.268$$

Average distance across voids, $\bar{l} = \frac{A}{n} = \frac{0.049}{9.1}$

$$\bar{l} = 0.00539 \text{ inch}$$

Hypothetical sphere radius, $r_h = \frac{3\bar{l}}{4} = \frac{3}{4}(0.00539)$

$$r_h = 0.00404 \text{ inch}$$

Specific surface, $\alpha = \frac{4n}{A} = \frac{4(9.1)}{0.049}$

$$\alpha = 743 \text{ sq. in./cubic inch}$$

Hypothetical number of spheres, $N = \frac{A\alpha^3}{36} = \frac{(743)^3 0.049}{36}$

$$N = 177{,}500 \text{ voids per cubic inch}$$

Radius of circumscribed sphere, $r_m = \frac{\sqrt{3}}{2}\left(\frac{p + A}{N}\right)^{1/3} = \frac{\sqrt{3}}{2}\left(\frac{0.268 + 0.049}{177{,}500}\right)^{1/3}$

TABLE 32

AIR-VOID CHARACTERISTICS OF LABORATORY CONCRETE BEAMS

Aggregate Designation	Beam Designation	Air-Void Characteristics of Hardened Concrete				
		Air Content, A, Percent	Voids per Inch, n	Specific Surface (Sq. In./Cu. In.)	Voids per Unit Vol, N (Voids per Cu. In.)	Spacing Factor, L (Inches)
A_1	A11	4.5	7.4	660	113,000	0.0073
	A22	4.9	[illegible]	740	178,000	0.0065
	A31	3.4	3.[illegible]	450	27,000	0.0128
	A32	3.2	3.5	440	24,000	0.0134
A_2	B11	4.6	7.1	710	[illegible]	0.0074
	B12	3.7	[illegible]	[illegible]	108,000	0.0080
	B21	4.8	[illegible]	720	155,000	0.0068
	B23	4.7	7.8	720	141,000	0.0071
	B31	3.8	4.3	450	31,000	0.0119
	B32	3.2	3.7	440	24,000	0.0134
A_3	C11	[illegible]	6.4	560	97,000	0.0081
	C13	4.[illegible]	7.2	570	114,000	0.0076
	C31	3.5	4.3	490	37,000	0.0114
	C32	3.2	4.7	590	57,000	0.0100
A_4	[illegible]	4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	4.8	8.1	670	[illegible]	[illegible]72
	432	2.[illegible]	[illegible]	520	37,000	0.0117
	[illegible]	[illegible].2	[illegible]	[illegible]	78,000	0.0090

TABLE 32--Continued

Aggregate Designation	Beam Designation	Air Content, A, Percent	Voids per Inch, n	Specific Surface (Sq. in./Cu. in.)	Voids per Unit Vol, N (Voids per cu. in.)	Spacing Factor, L (Inches)
		Air-Void Characteristics of Hardened Concrete				
A_4	441	3.3	3.4	440	20,000	0.0139
	442	3.7	3.4	370	16,000	0.0149
A_5	SA11	2.7	5.5	500	69,000	0.0092
	SA13	4.2	7.1	680	115,000	0.0076
	SA21	5.0	9.2	740	176,000	0.0065
	SA23	4.5	9.3	810	214,000	0.0061
	SA32	4.4	7.[illegible]	640	106,000	0.0080
	SA33	4.2	7.2	690	120,000	0.0075
A_6	SB11	10.3	22.2	860	581,000	0.0040
	SB12	9.9	20.5	830	498,000	0.0044
	SB21	5.5	11.5	840	285,000	0.0055
	SB22	5.5	10.7	780	229,000	0.0059
	SB31	3.8	4.7	520	45,000	0.0107
	SB33	3.3	5.1	540	52,000	0.0100
	SB41	4.4	8.4	740	156,000	0.0065
	SB42	4.6	8.[illegible]	710	1[illegible],000	0.0069
	SB52	[illegible]	11.7	820	293,000	0.0053
	SB53	6.2	12.8	820	306,000	0.0052
A_7	711	3.7	6.3	650	105,000	0.0080
	712	3.7	5.6	600	73,000	0.0090

$$r_m = 0.01052 \text{ inch}$$

Void spacing factor, $L = r_m - r_h = 0.01052 - 0.00404$

$$L = 0.00648 \text{ inch.}$$

Correlation Studies

In this study the durability of a given beam was affected by a number of variables in addition to the air-void characteristics. In particular, the coarse aggregate alone could be expected to produce considerable differences in durability among the beams, since six of the coarse aggregates were from sources with poor durability records. For a single concrete mix there is a given number of deleterious particles, and there are an infinite number of combinations in which these particles may be distributed in beams made from the mix. Thus, even within a mix large variations in durability could exist as a result of differences in the combinations of deleterious particles in the beams. Other variables such as efficiency of vacuum saturation, atmospheric temperature, skill of labor, and location of beams within the freezer could have an effect on the durability.

The principle objective of the study of the beams fabricated in the laboratory was to determine the relative importance of the five air-void characteristics in producing durable concrete. With the large differences in durability which could be introduced by the coarse-aggregate variable no effort should be made to predict durability from air-void characteristics alone. For that purpose special efforts should be made to control all variables other than the air-void characteristics. Since the effect of entrained air on the durability may be different when different aggregates are used, it is believed that by introducing the coarse aggregate

as a variable the results of the study have a wider application.

Hence, the beams examined in this study were regarded as a sample randomly selected from a universe of beams in which variables other than the entrained air exist. The correlation technique was used to study the various combinations of durability factors and air-void characteristics. Because of the coarse-aggregate variable, extremely high correlation coefficients would not be expected.

Linear Correlation--Individual Beams

First, the beams were considered as a sample from a population of beams without regard to their individual constituents or fabrication. The scatter diagrams using durability factor No. 3 with each of the five air-void characteristics are shown in Figures 6 through 10. The scatter diagrams using the other durability factors are presented in the Appendix.

Although it is possible that some curve other than a straight line would give a higher correlation between durability and a given air-void characteristic, it is believed that for the purpose of this study a straight line fitted by the least-squares method is satisfactory. A sample set of computations using the data for durability factor No. 3 and the spacing factor, L, is presented in Table 33. In these computations the correlation coefficient, r, the slope, b, and the regression line for durability factor on spacing factor are determined. Also the t-value for testing the significance of the correlation coefficient is computed. The formula for t was taken from page 88 of Statistical Theory in Research by Anderson and Bancroft (2).

The results of the computations for the twenty combinations of air-void characteristics and durability factors are summarized in Table 34.

SCATTER DIAGRAMS OF RELATION BETWEEN DURABILITY FACTOR NO. 3 AND VOID PROPERTIES

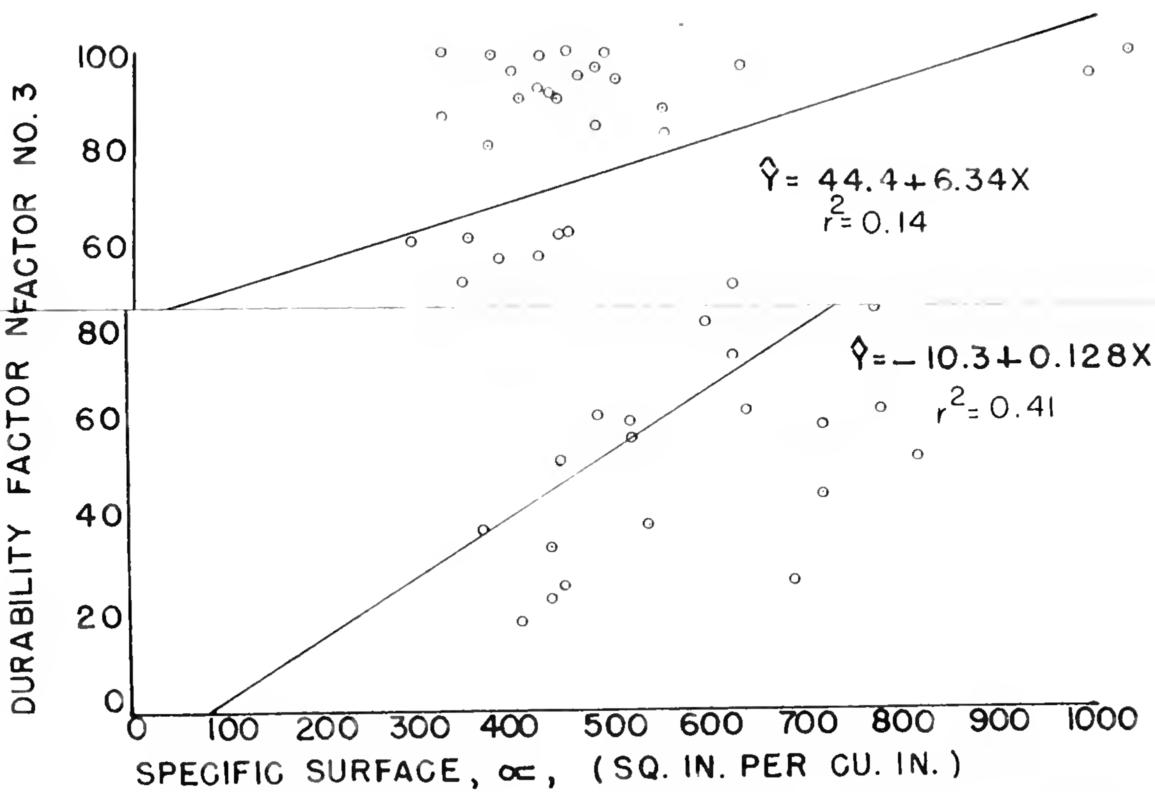


FIG. 8 DURABILITY FACTOR NO. 3 VERSUS SPECIFIC SURFACE.

SCATTER DIAGRAMS OF RELATION BETWEEN DURABILITY FACTOR NO 3 AND VOID PROPERTIES

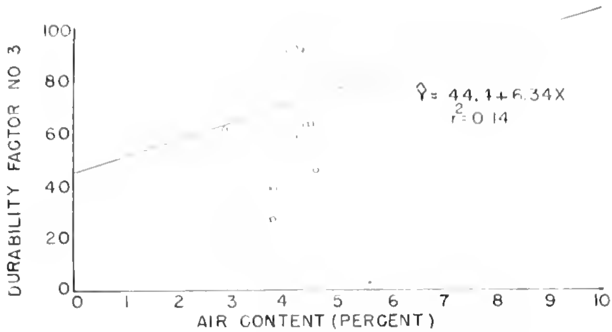


FIG 6 DURABILITY FACTOR NO 3 VERSUS AIR CONTENT

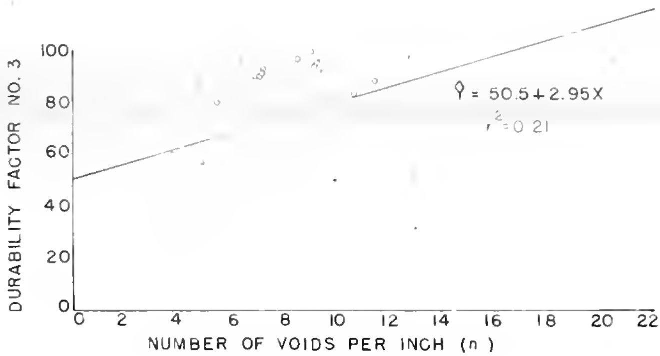


FIG. 7 DURABILITY FACTOR NO. 3 VERSUS NUMBER OF VOIDS PER INCH.

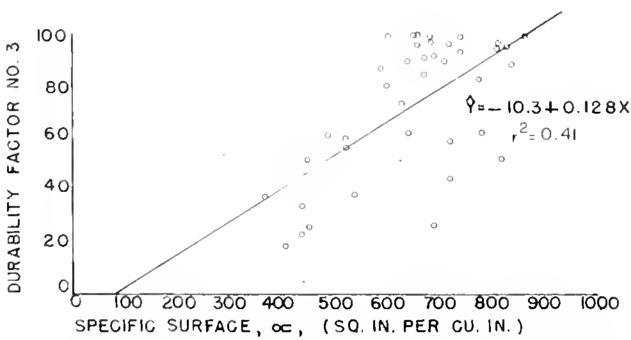


FIG. 8 DURABILITY FACTOR NO.3 VERSUS SPECIFIC SURFACE.

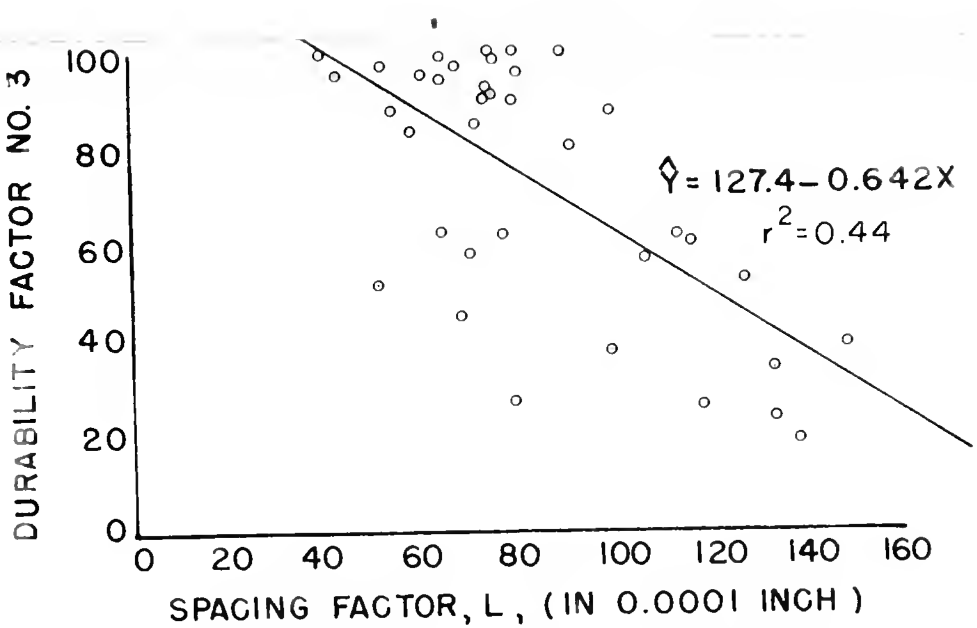


FIG. 10 DURABILITY FACTOR NO. 3 VERSUS SPACING FACTOR.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR NO.3 AND VOID PROPERTIES

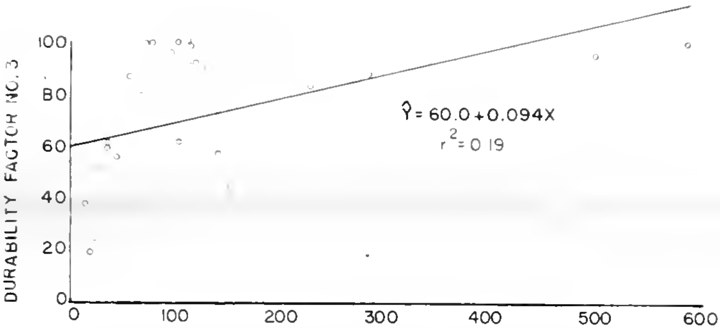


FIG. 9 DURABILITY FACTOR NO.3 VERSUS NO. OF VOIDS PER CUBIC INCH.

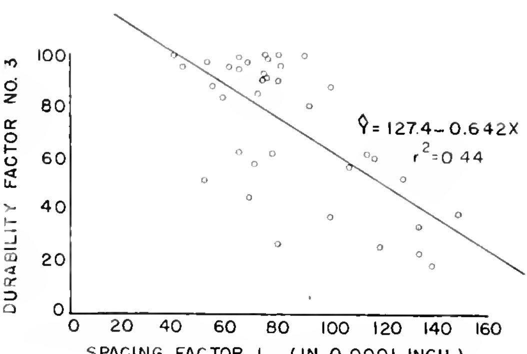


FIG. 10 DURABILITY FACTOR NO. 3 VERSUS SPACING FACTOR.

TABLE 3[illegible]

EXAMPLE OF COMPUTATION OF CORRELATION COEFFICIENT--LINEAR CORRELATION

Y	X
100	75
[illegible]	65
52	128
[illegible]	174
90	74
27	90
97	68
52	71
[illegible]	119
23	[illegible]
[illegible]	[illegible]
91	76
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	115
100	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	40
[illegible]	[illegible]
100	40
95	[illegible]
98	55
83	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
62	[illegible]
47	[illegible]
97	[illegible]
52	[illegible]
80	92
99	76
94	65
95	61
90	80
92	75

Y = [illegible] Factor [illegible]
X = Spacing Factor, L, [illegible] inch

$N = [illegible]$

$\sum X = [illegible]$

$\sum X^2 = [illegible]$

$\bar{X} = [illegible]$

$\sum Y = [illegible]$

$\sum Y^2 = [illegible]$

$\bar{Y} = [illegible]$

$\sum XY = [illegible]$

$SS(X) = \frac{N\sum X^2 - (\sum X)^2}{N}$

$SS(X) = [illegible]$

$SS(Y) = \frac{N\sum Y^2 - (\sum Y)^2}{N}$

$SS(Y) = [illegible]$

$SP(XY) = \frac{N\sum XY - (\sum X)(\sum Y)}{N}$

$SP(XY) = [illegible]$

$r^2 = \frac{[SP(XY)]^2}{[SS(X)][SS(Y)]}$

[illegible]

$r^2 = [illegible]$

$b = \frac{SP(XY)}{SS(X)}$

$b = [illegible]$

$Y = [illegible] - 0.[illegible](X - [illegible])$

$Y = 127.4 - 0.342X$

$t = r\sqrt{\frac{n-2}{1-r^2}} = 0.6[illegible]\sqrt{\frac{[illegible]}{1 - 0.441827[illegible]}}$

$t_{obs.} = 5.338$

TABLE 34

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY AND AIR-VOID CHARACTERISTICS--INDIVIDUAL BEAMS

Air-Void Characteristic	Durability Factor	$\overline{Y}$	$\overline{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{obs.}$	Significance	Variation Explained by Regression Line (Percent)
Air Content, A (Percent)	1	68.6	4.49	6.433	Y = 39.7 + 6.43X	0.3326	2.05	**	11.06
	2	58.5	4.49	6.696	Y = 28.4 + 6.70X	0.3050	1.92	*	9.30
	3	72.9	4.49	6.338	Y = 44.4 + 6.34X	0.3698	2.39	***	13.67
	4	62.9	4.49	6.916	Y = 31.8 + 6.92X	0.3440	2.20	**	11.84
Number of Voids per Inch, n	1	68.6	7.62	2.952	Y = 46.1 + 2.95X	0.4034	2.65	***	16.28
	2	58.5	7.62	3.088	Y = 35.0 + 3.09X	0.3718	2.40	***	13.82
	3	72.9	7.62	2.946	Y = 50.5 + 2.95X	0.4542	3.06	*****	20.63
	4	62.9	7.62	3.183	Y = 38.6 + 3.18X	0.4185	2.76	****	17.51
Specific Surface, α (Sq.in. per Cu.in.)	1	68.6	648.2	0.1268	Y = -13.6 + 0.127X	0.5575	4.03	*****	31.08
	2	58.5	648.2	0.1301	Y = -25.8 + 0.130X	0.5038	3.50	*****	25.38
	3	72.9	648.2	0.1284	Y = -10.3 + 0.128X	0.6370	4.96	*****	40.58
	4	62.9	648.2	0.1350	Y = -24.6 + 0.135X	0.5707	4.17	*****	32.57
Voids per Unit Volume, N (Thousands of Voids per Cu.in.)	1	68.6	137.4	0.0928	Y = 55.9 + 0.093X	0.3800	2.47	***	14.44
	2	58.5	137.4	0.0984	Y = 45.0 + 0.098X	0.3551	2.28	**	12.61
	3	72.9	137.4	0.0941	Y = 60.0 + 0.094X	0.4349	2.90	****	18.92
	4	62.9	137.4	0.1013	Y = 49.0 + 0.101X	0.3991	2.61	***	15.93

TABLE 34--Continued

Air-Void Characteristic	Durability Factor	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{obs.}$	Significance	Variation Explained by Regression Line (Percent)
Spacing Factor, L (0.0001 Inch)	1	68.6	84.9	-0.6428	Y = 123.2 - 0.643X	-0.5902	4.39	*****	34.83
	2	58.5	84.9	-0.6488	Y = 113.6 - 0.649X	-0.5247	3.70	*****	27.54
	3	72.9	84.9	-0.6416	Y = 127.4 - 0.642X	-0.6647	5.34	*****	44.18
	4	62.9	84.9	-0.6754	Y = 120.2 - 0.675X	-0.5966	4.46	*****	35.59

Note: Y = Durability Factor. X = Air-Void Characteristic.

$t_{0.95} = 1.69$ $t_{0.975} = 2.03$ $t_{0.9875} = 2.34$ $t_{0.995} = 2.72$ $t_{0.9975} = 2.99$

$*t_{obs.} > 1.69$ $**t_{obs.} > 2.03$ $***t_{obs.} > 2.34$ $****t_{obs.} > 2.72$ $*****t_{obs.} > 2.99$

The significance of the observed t for n-2 degrees of freedom is indicated in the table as well as the percentage of the variation in durability which is explained by the regression line. The regression lines have been plotted on the scatter diagrams.

Linear Correlation--Average Values for Each Mix

In order to study correlation between durability and air-void characteristics on a mix basis an analysis was made using the average values for each mix. Table 34 shows that in the case of each air-void characteristic the highest correlation coefficient was obtained using durability factor No. 3; therefore, for the study using average values for each mix it was decided to use only this durability factor. Since freeze-and-thaw data were available on three beams from each mix, the durability factor for each mix was taken as the average of the three beams. Durability factor No. 3 for the third beam in each mix is given in Table 35.

Average values for the durability factor and air-void characteristics for each mix are given in Table 36. The value for the durability factor for a given mix is the average of the values for the third beam which is given in Table 35, and for the first two beams which are given in Table 31. However, the value for each air-void characteristic is the average for the two beams from the given mix in Table 32. The scatter diagrams using durability factor No. 3 with each air-void characteristic are shown in Figures 11 through 15.

The same procedure was followed for the computation of slopes, correlation coefficients, and regression lines as that used in the individual beam study. The results are summarized in Table 37.

TABLE 35

DURABILITY FACTOR NO. 3 FOR THE THIRD BEAM IN EACH MIX

Aggregate Designation	Laboratory Mix Designation	Beam Designation	Durability Factor No. 3
A_1	33-A2	A23	99
	33-A3	A33	[illegible]
A_2	33-B1	B13	93
	33-B2	B23	77
	33-B3	[illegible]	21
A_3	33-C1	[illegible]	[illegible]
	33-C3	[illegible]	86
A_4	34-[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	34-[illegible]	[illegible]	34
A_5	SA-1	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	SA-[illegible]	[illegible]	[illegible]
A_6	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
A_7	[illegible]	[illegible]	[illegible]

TABLE [illegible]

AVERAGE AIR-VOID CHARACTERISTICS AND DURABILITY FACTOR NO. 3 FOR EACH LABORATORY MIX

Laboratory Mix Designation	Durability Factor No. 3	Air-Void Characteristics of Hardened Concrete				
		Air Content, A (Percent)	Voids per Inch, n	Specific Surface, α (sq. in./cu. in.)	Voids per Unit Volume, k (Voids per cu. in.)	Spacing Factor, L (Inches)
33-A2	39	[illegible]	[illegible]	700	[illegible]	0.0070
33-A3	40	[illegible]	[illegible]	[illegible]	[illegible]	0.0131
33-B1	70	[illegible]	[illegible]	[illegible]	[illegible]	0.0077
33-B2	84	4.5	[illegible]	[illegible]	[illegible]	0.0070
33-B3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0127
33-C1	94	[illegible]	[illegible]	[illegible]	[illegible]	0.0079
33-C3	78	[illegible]	[illegible]	[illegible]	[illegible]	0.0107
34-2	74	[illegible]	[illegible]	[illegible]	117,000	0.0075
34-3	70	[illegible]	[illegible]	[illegible]	[illegible]	0.0104
34-4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0144
SA-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0084
SA-2	94	[illegible]	[illegible]	[illegible]	[illegible]	0.0063
SA-3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0078
SB-1	[illegible]	10.1	21.4	[illegible]	341,000	0.0042
SB-2	85	[illegible]	11.1	[illegible]	[illegible]	0.0057
SB-3	51	[illegible]	[illegible]	[illegible]	[illegible]	0.0104
SB-4	57	[illegible]	[illegible]	[illegible]	170,000	0.0057
SB-5	82	[illegible]	[illegible]	[illegible]	[illegible]	0.0053
37-1	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].0035

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR NO.3 AND VOID PROPERTIES

AVERAGE VALUES FOR MIXES

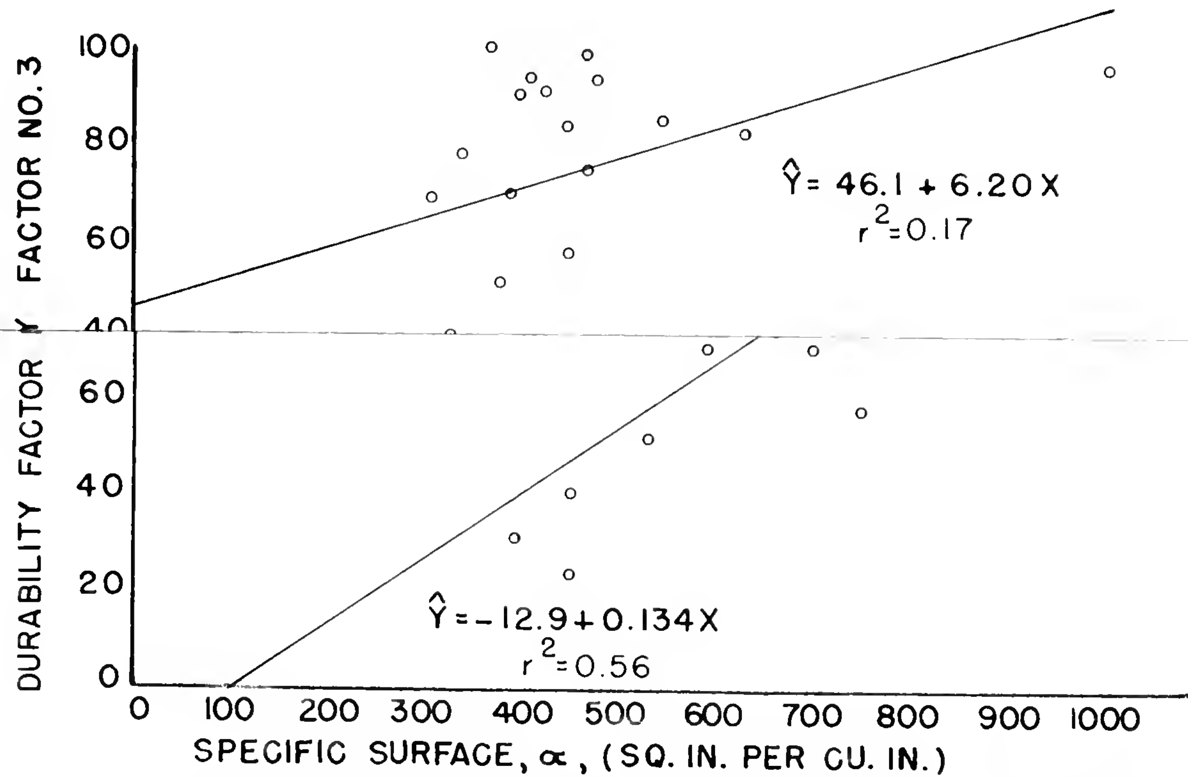


FIG. 13 DURABILITY FACTOR NO.3 VERSUS SPECIFIC SURFACE - AVERAGE VALUE FOR MIXES.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR NO.3 AND VOID PROPERTIES

AVERAGE VALUES FOR MIXES

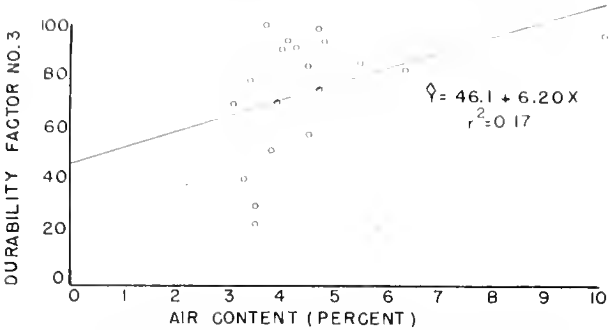


FIG. 11 DURABILITY FACTOR NO.3 VERSUS AIR CONTENT - AVERAGE VALUES FOR MIXES.

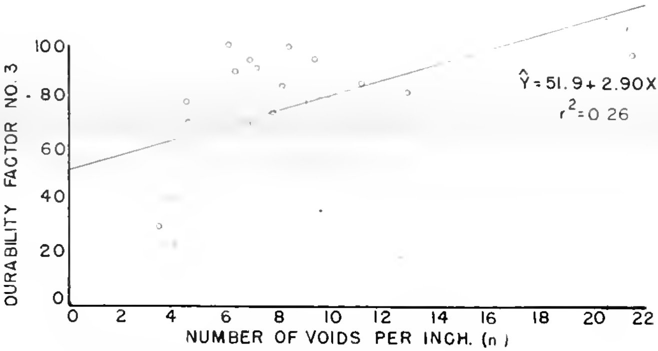


FIG. 12 DURABILITY FACTOR NO.3 VERSUS NO. OF VOIDS PER INCH - AVERAGE VALUES FOR MIXES.

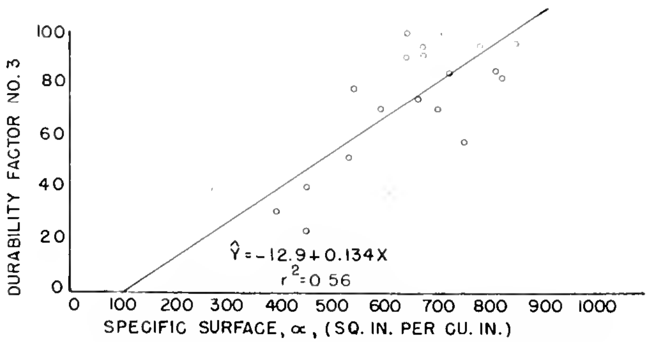


FIG. 13 DURABILITY FACTOR NO.3 VERSUS SPECIFIC SURFACE - AVERAGE VALUE FOR MIXES.

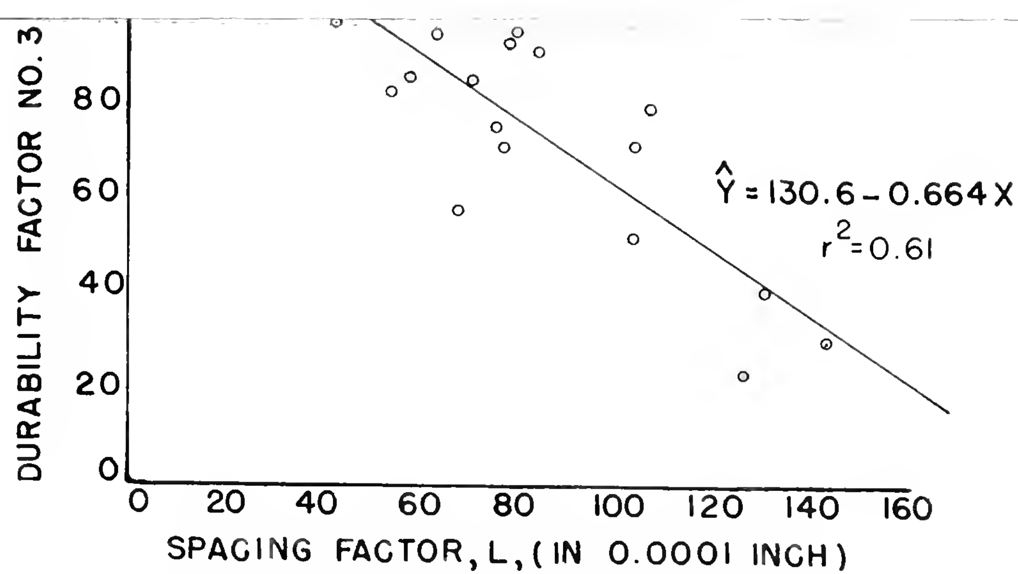


FIG. 15 DURABILITY FACTOR NO.3 VERSUS SPACING FACTOR—AVERAGE VALUES FOR MIXES.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR NO.3 AND VOID PROPERTIES

AVERAGE VALUES FOR MIXES

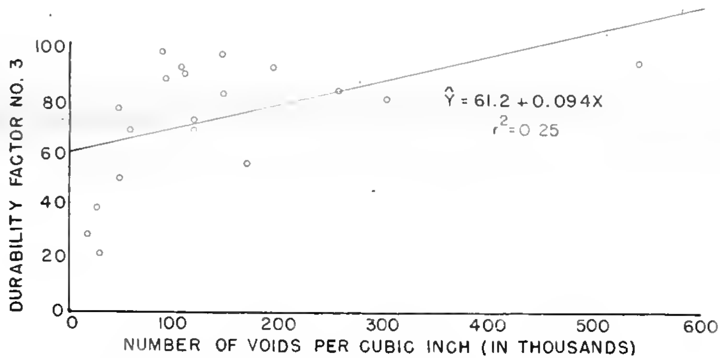


FIG. 14 DURABILITY FACTOR NO.3 VERSUS NO. OF VOIDS PER CUBIC INCH— AVERAGE VALUES FOR MIXES.

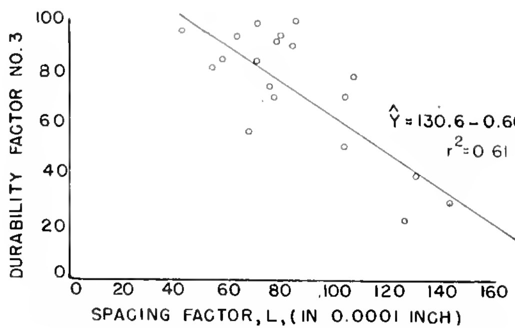


FIG. 15 DURABILITY FACTOR NO.3 VERSUS SPACING FACTOR— AVERAGE VALUES FOR MIXES.

TABLE 37

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY AND AIR-VOID CHARACTERISTICS--AVERAGE VALUES FOR EACH MIX--DURABILITY FACTOR NO. 3

Air-Void Characteristic	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{obs.}$	Significance	Variation Explained by Regression Line (Percent)
Air Content, A (Percent)	74.1	4.51	6.202	Y = 46.1 + 6.20X	[illegible]	1.87	*	1[illegible].09
Number of Voids Per Inch, n	74.1	7.64	2.903	Y = [illegible] + [illegible]X	0.51[illegible]	[illegible].47	***	26.40
Specific Surface, α (Sq.In. per Cu.In.)	74.1	650.5	[illegible]	Y = [illegible]	[illegible]	[illegible]	*****	55.66
Voids per Unit Volume, N (Thousands of Voids per Cu.In.)	74.1	137.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**	[illegible].53
Spacing Factor, L (0.0001 Inch)	74.1	[illegible]	[illegible]	Y = [illegible]	[illegible]	[illegible]	*****	[illegible]

Note: Y = Durability Factor. X = Air-Void Characteristic.

$t_{0.95} = 1.74$ $t_{0.975} = [illegible]$ $t_{[illegible]} = [illegible]$ $t_{[illegible]} = [illegible]$ $t_{[illegible]} = 3.22$

$*t_{obs.} > 1.74$ $**t_{obs.} > [illegible]$ $***t_{obs.} > [illegible]$ $****t_{obs.} > [illegible]$ $*****t_{obs.} > 3.22$

Discussion of Correlation Studies

The graphs of durability factor No. 3 plotted against the five air-void characteristics (Figures 6 through 15) show considerable scatter. Some of this scatter would be expected to result from the coarse-aggregate variable. Inspection of the scatter diagrams alone would lead one to conclude that little correlation exists between the total air content and durability for the beams examined in this study. In the past the total air content has been the air-void characteristic most used in determining the air requirements for frost-resistant concrete.

The graphs plotted with average values for each mix show less scatter than the graphs plotted with the values for the individual beams. This results from eliminating the large differences in durability between beams within the same mix by means of averaging the individual values. A large amount of this difference in durability within a mix can be attributed to the coarse aggregate in that differences in the combinations of deleterious particles in the beams results in variations in durability.

The air-void characteristics (specific surface and spacing factor) which are computed from equations containing both air content and number of voids per inch show the smallest amount of scatter. This indicates the importance of the interaction of these two-characteristics in producing durable concrete.

Inspection of Tables 34 and 37, also, shows the importance of the interaction of air content and number of voids per inch in producing durable concrete. The specific surface and void spacing factor gave considerably higher correlation coefficients than the other three characteristics. The correlation between each of these two characteristics and

the four durability factors are shown to be highly significant at the 99.75 percent confidence level. For example, from Table 34, using durability factor No. 3 it can be seen that 41 percent of the differences in durability can be attributed to differences in the specific surface, while 44 percent of the differences in durability can be attributed to differences in spacing factor. These percentages are increased to 56 percent and 61 percent, respectively, when the average values for a mix are used.

The highest correlation coefficients are obtained using durability factor No. 3. Durability factor No. 3 is defined as the area under the curve (dynamic E as a percent of the original E plotted against cycles of freezing and thawing) to the left of the 200th cycle and above the 50 percent dynamic E line, expressed as a percentage of the total area to the left of the 200th cycle and above the 50 percent dynamic E line. This particular durability factor gives higher values for durability as well as smaller differences in durability between beams. This indicates that methods of measurement of durability which tend to classify concrete into only two groups--either durable or non-durable--without intermediate values, are not as satisfactory for correlation studies as methods which measure differences in durability in small increments.

Although there may be a better way to express the size and distribution of the air voids in portland cement paste than the spacing factor used in this study, the results of the correlation studies essentially substantiate the accepted theory on the action of entrained air in producing frost-resistant concrete.

SUMMARY OF RESULTS

The results of the work completed in this investigation may be summarized in the following manner.

1. The measurement by the linear traverse technique of the air content and number of voids per inch of a particular beam may be considered as one long traverse without regard to the position or length of the individual traverses. The standard error of the mean is approximately the same (0.3 for the beams examined in this study) whether four-, six-, eight-, or ten-inch traverses are used as long as the total length of the traverses is the same.

2. For the beams and cores examined in this study, the selection of 200 inches of traverses gave values for the air content within ± 0.5 percent of the true value and the number of voids per inch within ± 0.5 void per inch of the true value at the 90 percent confidence level.

3. The time required to polish one surface and observe one hundred inches of traverses on that surface was approximately four hours.

4. The concrete pavements constructed without the purposeful entrainment of air showed an average air content of 2.0 percent for the pavement with crushed limestone for coarse aggregate and an average air content of 1.7 percent for the pavement with glacial gravel for coarse aggregate. For both types of pavement the average value for the number of voids per inch was found to be 0.8.

5. The analysis of variance indicated that neither the air content nor the number of voids per inch for the pavement constructed with crushed limestone was significantly different from the corresponding value for the pavement constructed with glacial gravel for coarse aggregate.

6. A study of the core data with regard to the development of a sampling plan for pavements suggested simple random sampling along the stretch of pavement with measurements being made on one surface per core. For pavements similar to those examined in this study, n cores should give the air content as

$$\bar{X} \pm t \sqrt{\frac{0.26}{n}} ;$$

and, the number of voids per inch as

$$\bar{X} \pm t \sqrt{\frac{0.05}{n}} ;$$

with t having n - 1 degrees of freedom.

7. The correlation studies of the relationship between each of the five air-void characteristics and durability indicated the void spacing factor to be the most highly correlated with durability factor. Using durability factor No. 3 and data on individual beams, 44 percent of the differences in durability could be explained by differences in the void spacing factor. Using average values for each mix, 61 percent of the differences in durability could be explained by differences in the void spacing factor.

8. The specific surface was almost as highly correlated with durability as the void spacing factor with 41 percent of the variation in durability factor No. 3 being explained by the differences in the specific surface when the data on the individual beams was used. Using average values for each mix 56 percent of the variation in durability factor No. 3 could be explained by differences in the specific surface.

9. The five air-void characteristics ranked in the order of their correlation with durability beginning with the one showing the best cor-

relation are: (a) spacing factor, (b) specific surface, (c) number of voids per inch, (d) hypothetical number of voids per cubic inch, and (e) total air content.

CONCLUSIONS

Based on the results of this study, the following conclusions seem reasonable.

1. The linear traverse technique is a satisfactory and reliable method for determining the air content and number of voids per inch of hardened concrete when employed by a properly trained technician.

2. Since neither the air content nor the number of voids per inch for the pavement constructed with crushed limestone was significantly different from the corresponding value for the pavement constructed with glacial gravel, it may be concluded that the differences in field performance of these pavements were not due to differences in the entrapped air.

3. For the sampling of concrete pavements the study of the variability of the air content and number of voids per inch suggests simple random sampling along the stretch of pavement with measurements being made on one surface per core.

4. The accepted theoretical explanation of the action of entrained air in producing frost-resistant concrete demonstrates the importance of the size and distribution of the air voids. The correlation studies of the relationship between each of the air-void characteristics and durability show the void spacing factor to be the most highly correlated with durability factor. Thus, this investigation essentially substantiates the theory.

5. Since the specific surface was almost as highly correlated with durability factor as the void spacing factor, either of these two characteristics is probably a satisfactory guide for determining the air requirements for frost-resistant concrete.

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APPENDIX

SCATTER DIAGRAM OF RELATIONSHIP BETWEEN DURABILITY FACTORS AND AIR CONTENT

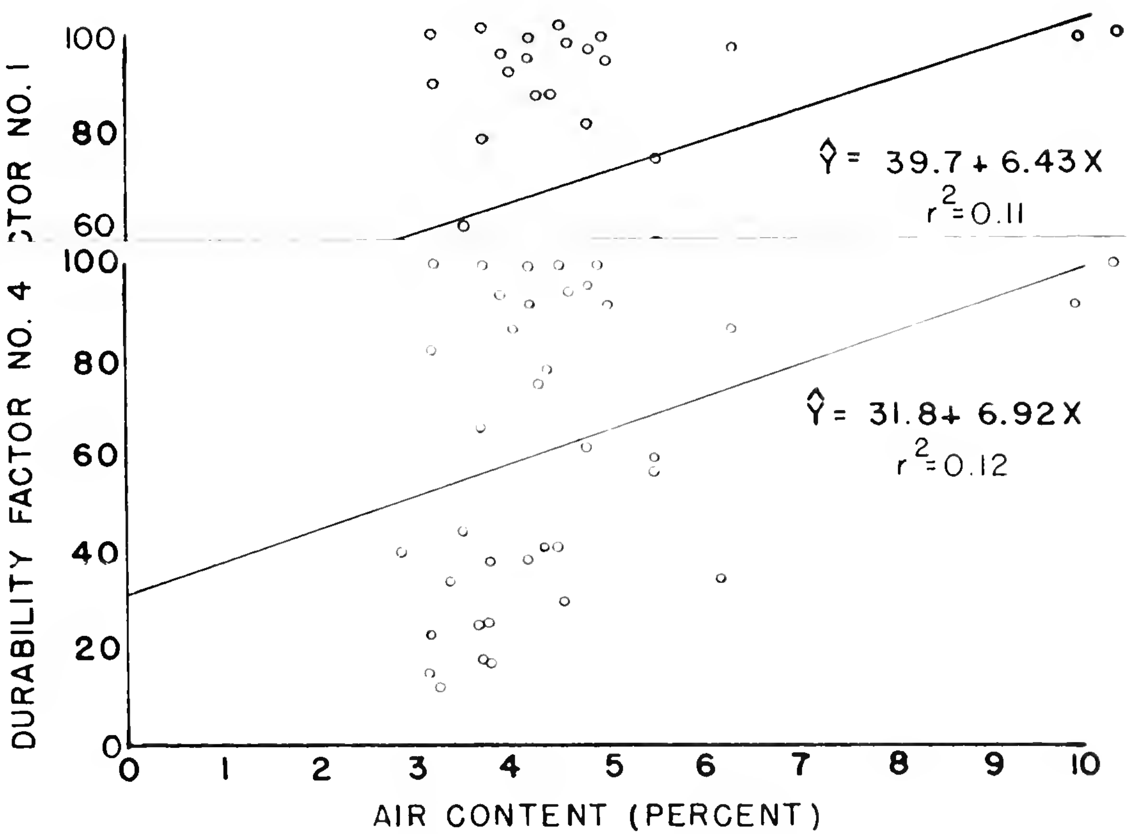

FIG. B-3 DURABILITY FACTOR NO. 4 VERSUS AIR CONTENT.

SCATTER DIAGRAM OF RELATIONSHIP BETWEEN DURABILITY FACTORS AND AIR CONTENT

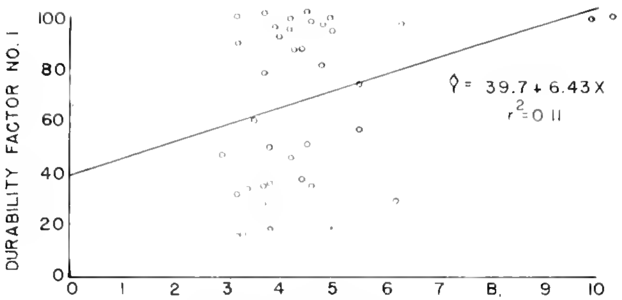

FIG. B-I DURABILITY FACTOR NO. I VERSUS AIR CONTENT.

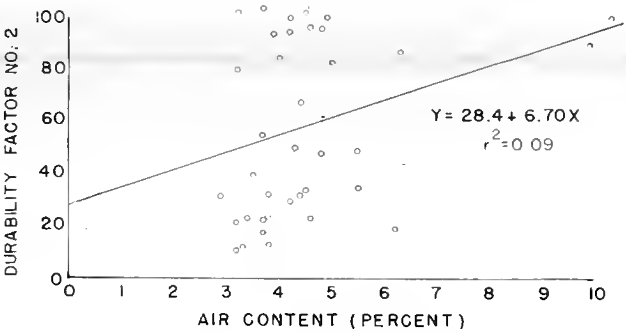

FIG. B-2 DURABILITY FACTOR NO. 2 VERSUS AIR CONTENT

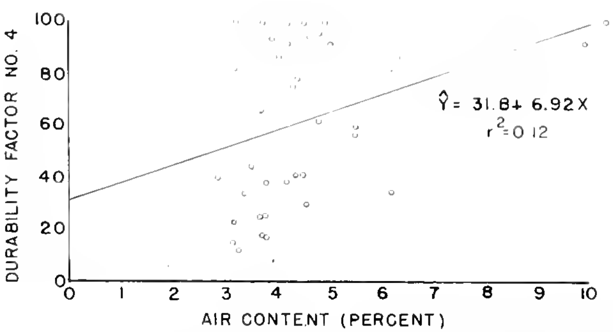

FIG. B-3 DURABILITY FACTOR NO. 4 VERSUS AIR CONTENT.

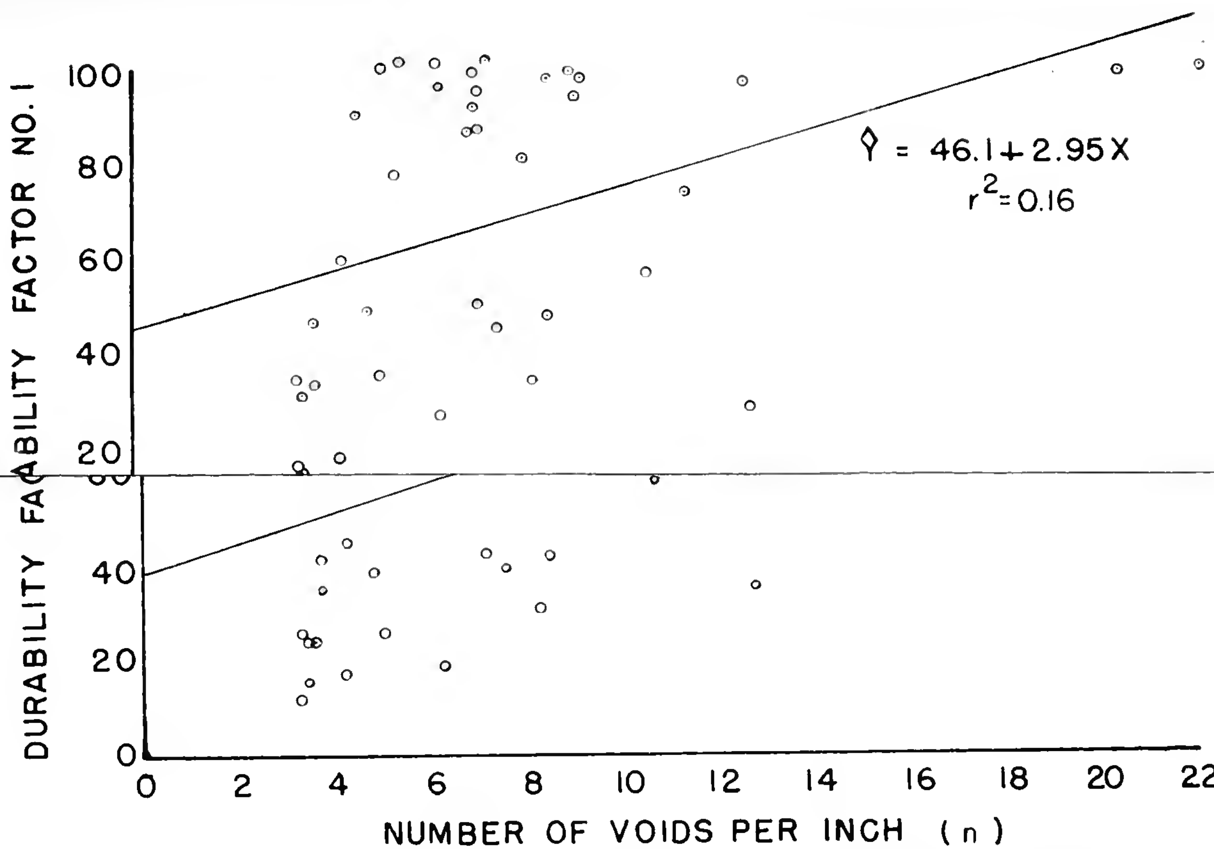

FIG. B-6 DURABILITY FACTOR NO. 4 VERSUS NUMBER OF VOIDS PER INCH.

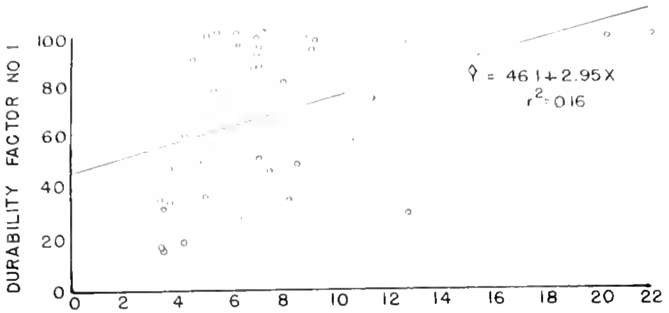

FIG. B-4 DURABILITY FACTOR NO. 1 VERSUS NUMBER OF VOIDS PER INCH.

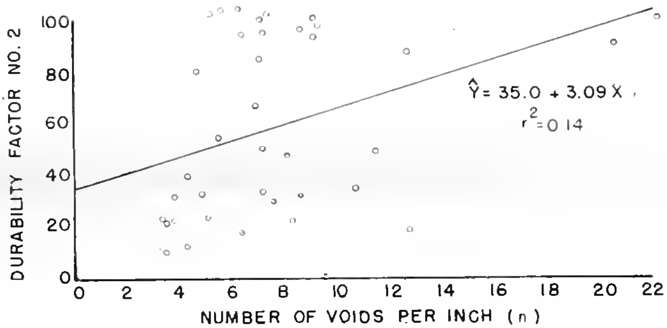

FIG. B-5 DURABILITY FACTOR NO. 2 VERSUS NUMBER OF VOIDS PER INCH.

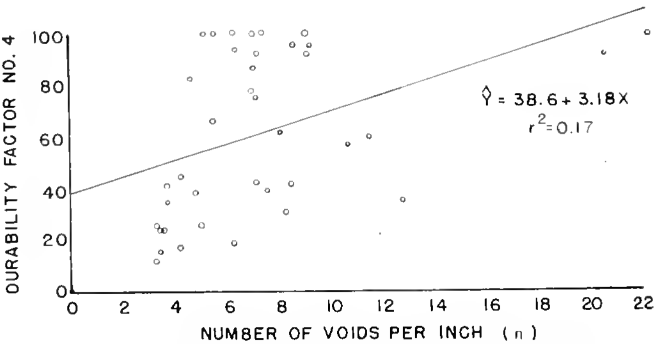

FIG. B-6 DURABILITY FACTOR NO. 4 VERSUS NUMBER OF VOIDS PER INCH.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND SPECIFIC SURFACE

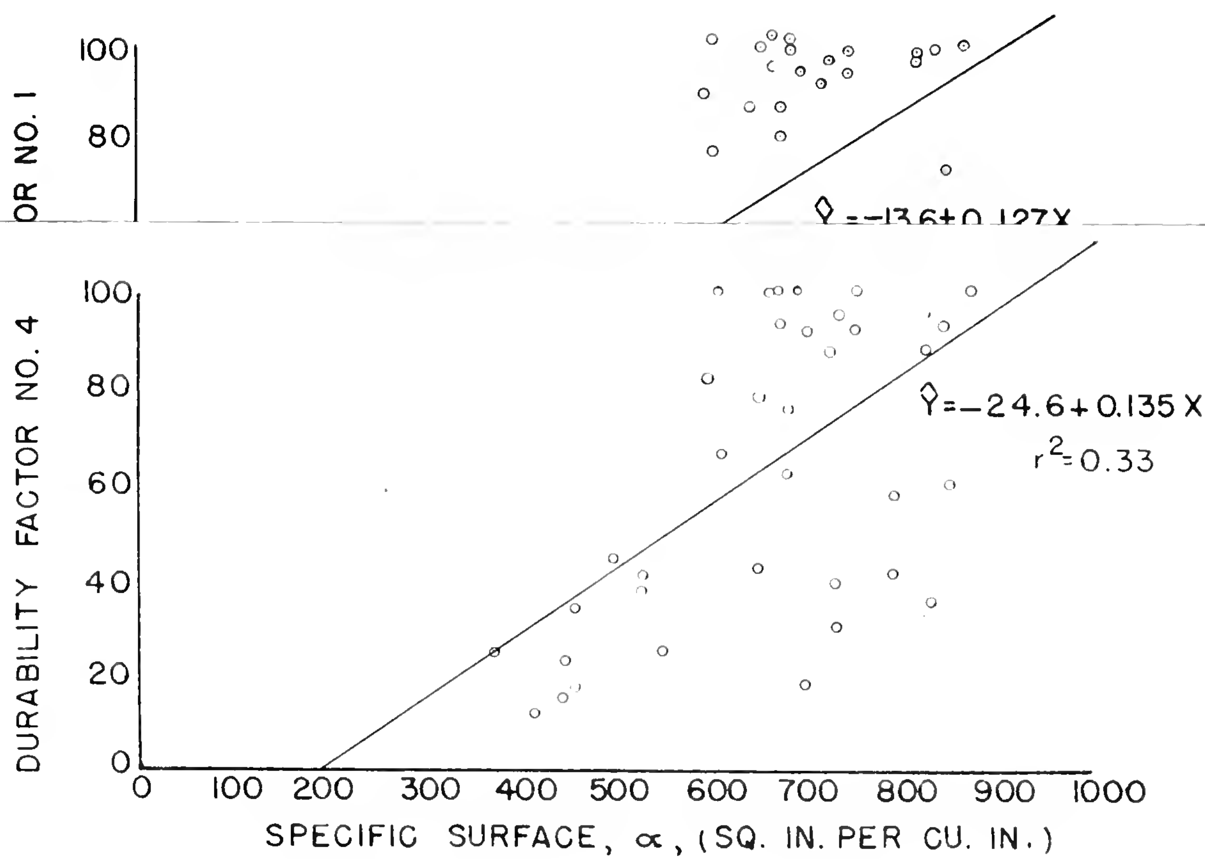

FIG. B-9 DURABILITY FACTOR NO. 4 VERSUS SPECIFIC SURFACE.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND SPECIFIC SURFACE

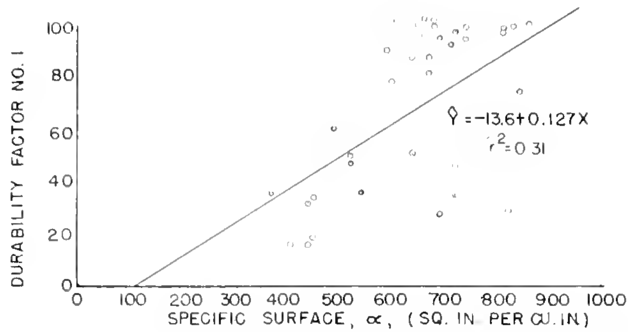

FIG 8-7 DURABILITY FACTOR NO. 1 VERSUS SPECIFIC SURFACE

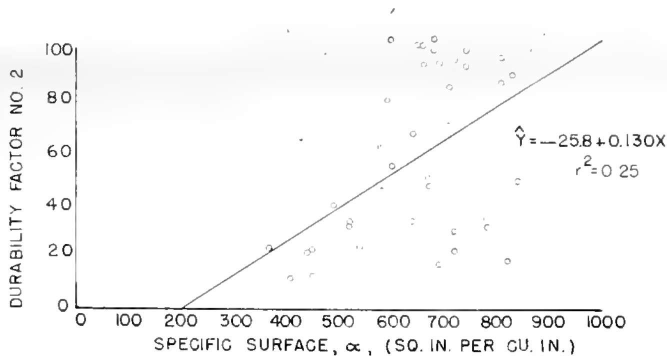

FIG 8-8 DURABILITY FACTOR NO. 2 VERSUS SPECIFIC SURFACE.

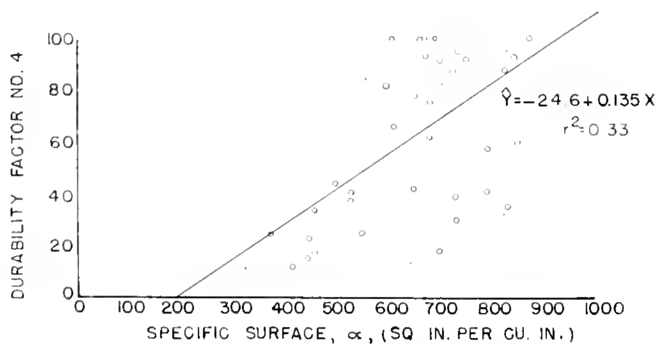

FIG. 8-9 DURABILITY FACTOR NO. 4 VERSUS SPECIFIC SURFACE

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND VOIDS PER CUBIC INCH

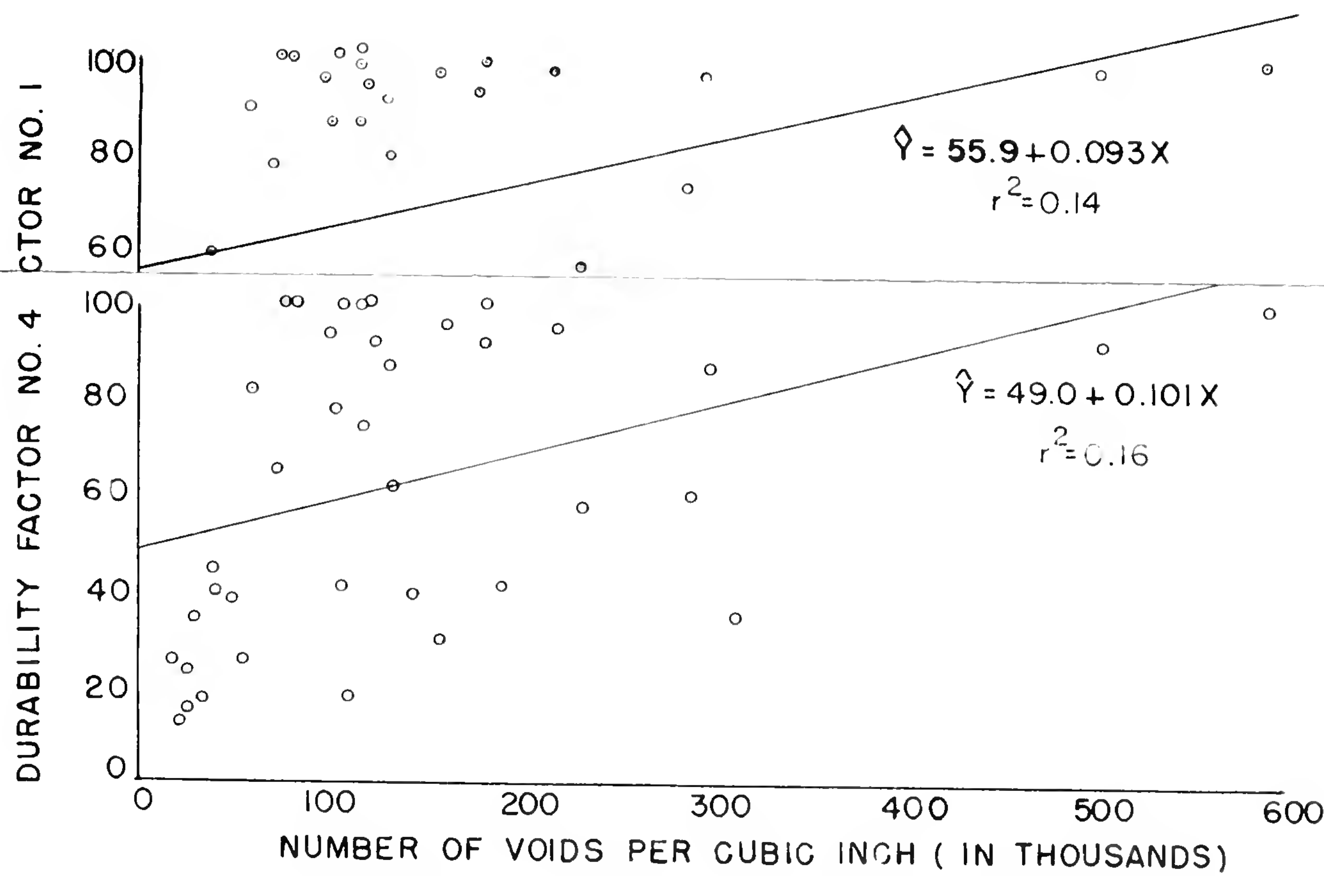

FIG. B-12 DURABILITY FACTOR NO.4 VERSUS VOIDS PER CUBIC INCH.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND VOIDS PER CUBIC INCH

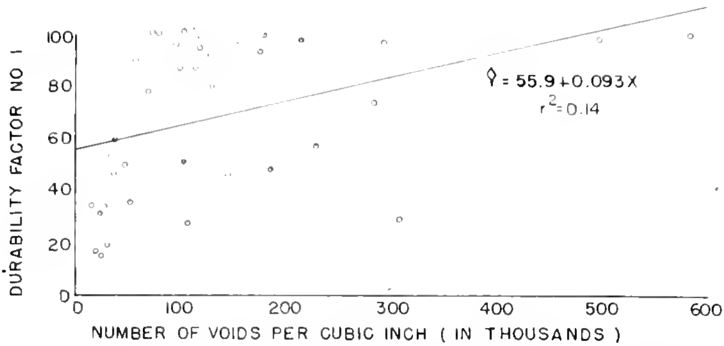

FIG. B-10 DURABILITY FACTOR NO.1 VERSUS VOIDS PER CUBIC INCH.

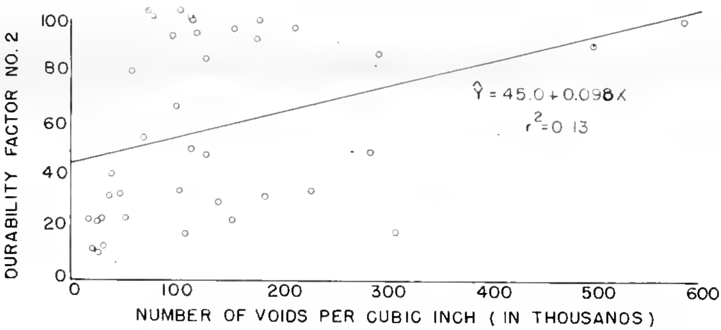

FIG. B-11 DURABILITY FACTOR NO. 2 VERSUS VOIDS PER CUBIC INCH.

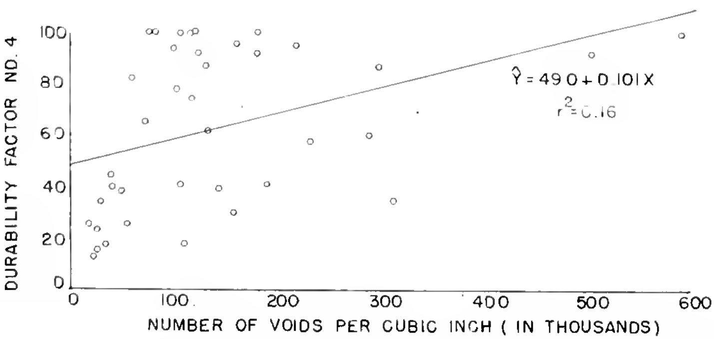

FIG. B-12 DURABILITY FACTOR NO 4 VERSUS VOIDS PER CUBIC INCH.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND SPACING FACTOR

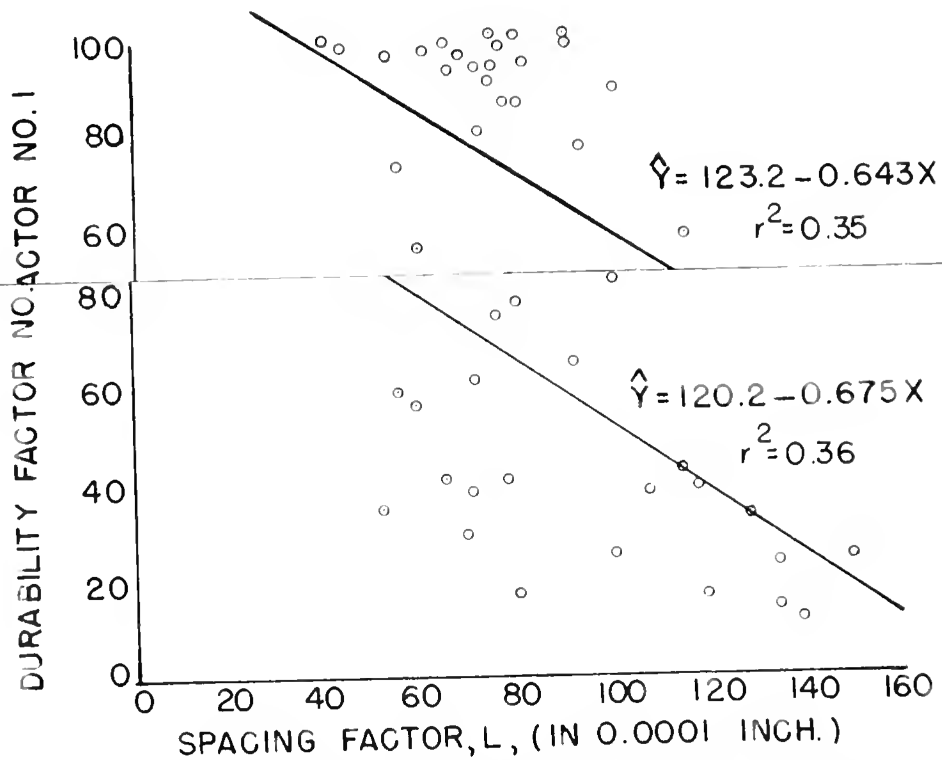

FIG. B-15 DURABILITY FACTOR NO. 4 VERSUS SPACING FACTOR.

SCATTER DIAGRAMS OF RELATIONSHIP BETWEEN DURABILITY FACTOR AND SPACING FACTOR

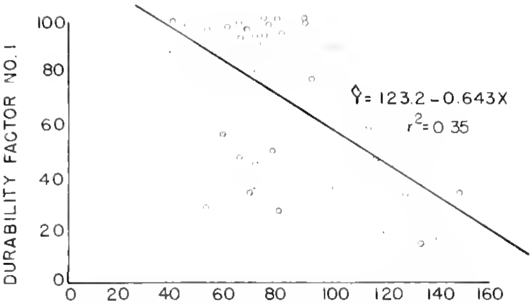

FIG. B-13 DURABILITY FACTOR NO. 1 VERSUS SPACING FACTOR.

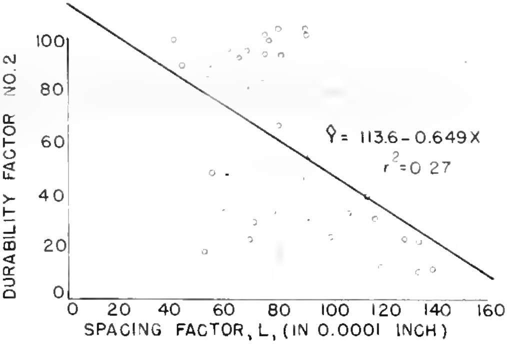

FIG. B-14 DURABILITY FACTOR NO. 2 VERSUS SPACING FACTOR.

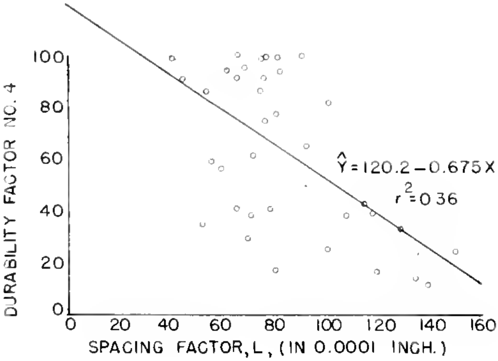

FIG. B-15 DURABILITY FACTOR NO. 4 VERSUS SPACING FACTOR.